INFLUENCE OF LOAD CONDITIONS IN MEMBRANE SPRING-LOADED CYLINDER ON DYNAMIC CHARACTERISTICS OF PNEUMATIC BRAKE SYSTEM

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Abstract. The article presents selected problems of pneumatic brake systems, which are one of the most important systems responsible for the active safety of heavy vehicles. Different types of vehicle braking in various load characteristics resulting from the road surface conditions are described briefly. It is clear that braking effectiveness depends strongly on the type of braking, i.e. on the load characteristics of pneumatic brake cylinders. Therefore, analytical and experimental studies of such systems are timely and important. The article presents results of experimental tests of a pneumatic drive system with two membrane spring-loaded cylinders used in brake systems of heavy vehicles. Each cylinder has been equipped with a specially designed mechanism changing load characteristics of the cylinder piston to simulate the braking process in various tire grip conditions. The obtained results present time histories of pressure and piston displacement for various load configurations of membrane spring-loaded cylinders. These experimental results can be used to prepare and verify a mathematical model of vehicle braking processes in various road surface conditions. Such model can be useful for design purposes of novel pneumatic brake systems.

Keywords: pneumatic brake system, mechanism for changing load characteristics, membrane spring-loaded cylinder.

Introduction

According to the European Transport Safety Council (ETSC) report on pedestrian safety in the European Union, the number of people seriously injured on Europe's roads was 135,000 in 2014 [1]. The ETSC report presents different ways to prevent such a large number of fatal blindsided crashes [2], such as intelligent safety car systems or special facilities to improve visibility in front of a car.

Braking processes play a key role in road traffic safety problems. A possibility to stop a car depends on many factors [3], such as: vehicle speed, brake system status, various additional electronic systems to improve braking, road surface status, driver's perception-reaction times or his/her way of pressing the braking pedal.

The brake system is one of the most important systems decisive to active safety of mechanized vehicles [4-6]. Growth of the speed of mechanized vehicles and the sharp increase in their number in recent years necessitate work with the objective of improving the effectiveness and reliability of brake operation [4; 7-9]. Last years resulted with a rapid development of electronic systems supporting car braking, such as: ABS (Anti-Lock Braking Systems), ASR (Acceleration Slip Regulation) systems, BAS (Brake Assist Systems), City Safety systems, EBD (Electronic Brakeforce Distribution) systems. Designing and research work on brake systems enables, among other things, continuous development of the design of increasingly modern vehicle brakes with effectiveness of operation approaching the limits dictated by the tractive adhesion of tires to the roadway and limiting the danger of vehicle wheel slip during braking. Experimental tests that make it possible to completely evaluate the dynamic properties of a designed brake system are a significant part of the conducted research.

Fundamentals of mathematical modeling of pneumatic and hydraulic vehicle brake systems have been developed by Metlyuk and Avtushko [10]. They proposed a novel air flow rate function, the so called hyperbolic function, to include the resistive properties of various nozzles, orifices, valves etc. that can be met in pneumatic systems. By using this function the efficiency of calculations has been increased considerably, as the developed hyperbolic function does not have a discontinuity point between the under-critical and over-critical air flows. Kaminski [7, 8], and Kulesza and Siemieniako [11] used this function to develop mathematical models of complicated components of pneumatic brake systems, such as: an emergency valve, a trailer brake control valve, a brake valve and a relay valve. The numerical results obtained with the developed models have been verified experimentally and have confirmed the great efficiency as well as accuracy of the assumed modeling techniques.

Another approach was proposed by He et al. [5], who used the Modelica software to develop a mathematical model of the brake valve. They utilized the traditional flow rate function in the form proposed originally by Saint-Wenant and Wantzel. The same form of the flow rate function has been used by Subramanian et al. [6] to calculate the pressure changes in a pneumatic subsystem of an S-cam air brake system. Mithun et al. [9] adopted the commercial software AMESim [12] to model and simulate a pneumatic brake system used in heavy vehicles. They emphasized the simplicity and efficiency of modeling when using this software, but the results obtained by them were not verified experimentally. Thus, the accuracy of the results obtained with the proposed software cannot be evaluated.

The objective of the present article is to determine the effect of the load conditions in a membrane, spring-loaded brake cylinder on the dynamic characteristics of a pneumatic drive system, and thus, on the progression of the braking process. Experimental tests were conducted under laboratory conditions with the application of a specially designed loading mechanism used to change the load characteristics of the cylinder.

This article presents a specially designed loading mechanism enabling a change of the load characteristics of pneumatic brake cylinders used in heavy vehicles [11; 13]. The results of the experimental tests of the braking process, conducted under laboratory conditions and accounting for different types of braking force configurations, are presented. The results of these tests will serve for verification of mathematical models of the braking process in the future. The results of time history analysis of pressure and piston displacement are presented for various loading configurations of membrane, spring-loaded cylinders.

Materials and methods

1. Load characteristics of a vehicle brake cylinder

Fig. 1 presents example load characteristics of a pneumatic brake cylinder [10].

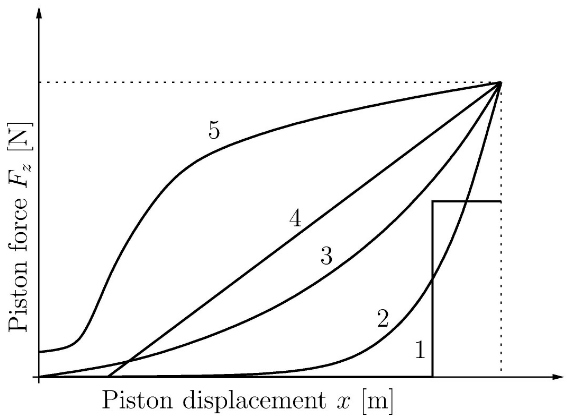

Fig. 1. **Example load characteristics of vehicle brake cylinder for different types of braking:** 1 – with no vehicle load; 2 – on a very slippery pavement; 3 – on a road covered in snow; 4 – on dew-covered asphalt; 5 – on dry asphalt

Characteristic curve no. 1 presents the load of a vehicle brake cylinder that is not under load, with wheels turning freely. In this case, the vehicle is found on a lift with its wheels not pressed to the base. Initially, no force acts on the brake system. At the instant of braking, the force increases to its maximum value in one step. Characteristic curve no. 2 represents a vehicle braking on very slippery pavement. Characteristic curve no. 3, similar to the previous characteristic curve, shows braking of a vehicle on a road covered in snow. Characteristic no. 4 is a linear characteristic. It demonstrates the situation of braking on dew-covered asphalt. The final characteristic, no. 5, presents the situation when a vehicle brakes on dry asphalt with good tractive adhesion.

2. Structure and operation principle of the loading mechanism

The designed loading mechanism, used to change the load characteristics of the brake cylinders of heavy vehicles, is presented in Fig. 2 [13].

The main components of the loading mechanism are: a system of twelve exchangeable coil springs (6) and a flat spring (9). The executive component in the mechanism is the membrane, spring-loaded brake cylinder (1), which presses upon moving beams (11), (13) under the action of compressed air, which causes tensioning of springs. Other components of the mechanism, marked in Figure 2, are: the cylinder piston (4), constructional frame (10), fixed constructional beam (7), latch I (3), latch II (8), nut (5) for changing the turn point of the load characteristic (Fig. 3b), guides (12), nut adjusting the orientation of the latch I (2).

Any set-up configuration of coil springs (6) may be used, but the springs are to be arranged symmetrically, in pairs, so that equilibrium of the mechanism of beams (11) and (13) is maintained. After compressed air is supplied or discharged (depending on the cylinders used), the membrane, spring-loaded cylinder (1) applies tension to springs (6) or (9) via beams (11) and (13), which slide on guides (12). The adjustment nut (5) serves to block the moving beam (13) with the cylinder piston (4). This is to set the desired shape of the load characteristic.

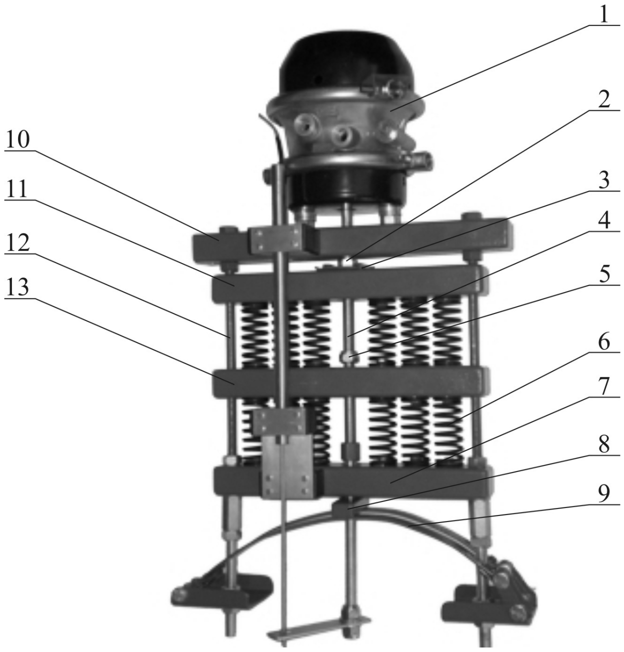

Fig. 2. **Loading mechanism enabling change of load characteristic of brake cylinders:** 1 – spring-loaded brake cylinder; 2 – nut adjusting the orientation of the latch I; 3 – latch I; 4 – cylinder piston; 5 – nut; 6 – system of twelve exchangeable coil springs; 7 – fixed constructional beam; 8 – latch II; 9 – flat spring; 10 – constructional frame; 11 – moving beam; 12 – guides; 13 – moving beam

Fig. 3a presents an example configuration of springs used to achieve the load characteristic shown in Fig. 3b.

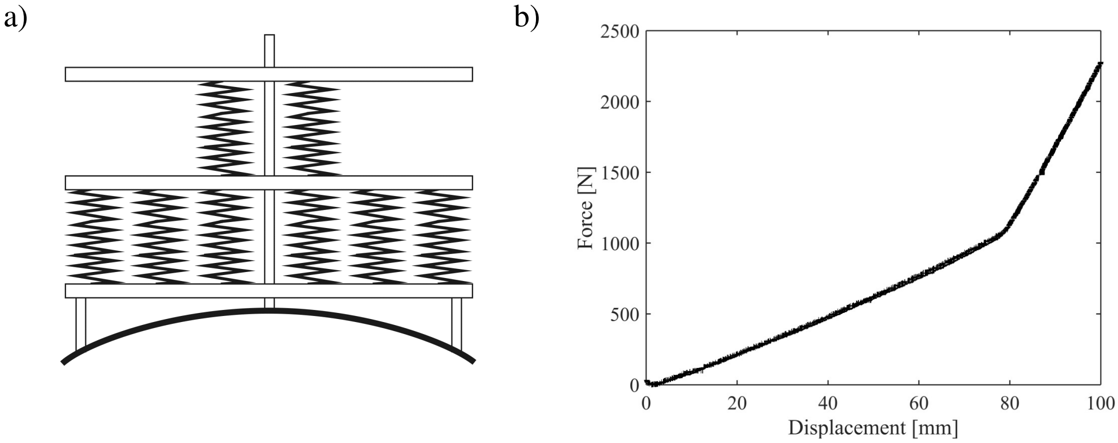

Fig. 3. **Loading mechanism:** a – example configuration of springs; b – corresponding load characteristic

3. Time history analysis of pressure and cylinder piston displacement for various loading configurations of membrane, spring-loaded cylinders

Fig. 4 presents a schematic diagram of the laboratory stand. Conduits connecting cylinders to the T-pipe have a length of 0.4 m, and the conduit connecting the T-pipe on the outlet of cylinders with the solenoid valve has a length of 2 m. The inner diameter of connecting pneumatic conduits is equal to 12 mm.

The system is supplied with compressed air by the compressor (1). Air flows through the compressed air preparation block (2). From the block (2), air flows through the cut-off valve (3) to the compressed air tank (4), where the pressure value in the tank is indicated by the pressure gauge (5) and registered by the pressure transducer (6). Next, compressed air is supplied to the inlet of the three-way dual-position valve (7). The valve (7) is controlled with 24V voltage and enables flow of compressed air to membrane spring-loaded cylinders (8), (9). A pressure measurement transducer (16) is found on the outlet of the valve (7). Pressure transducers (6) are also installed on the supply tank and in the chambers of membrane spring-loaded cylinders (10), (11). Cylinder piston displacements are registered by displacement transducers (12), (13).

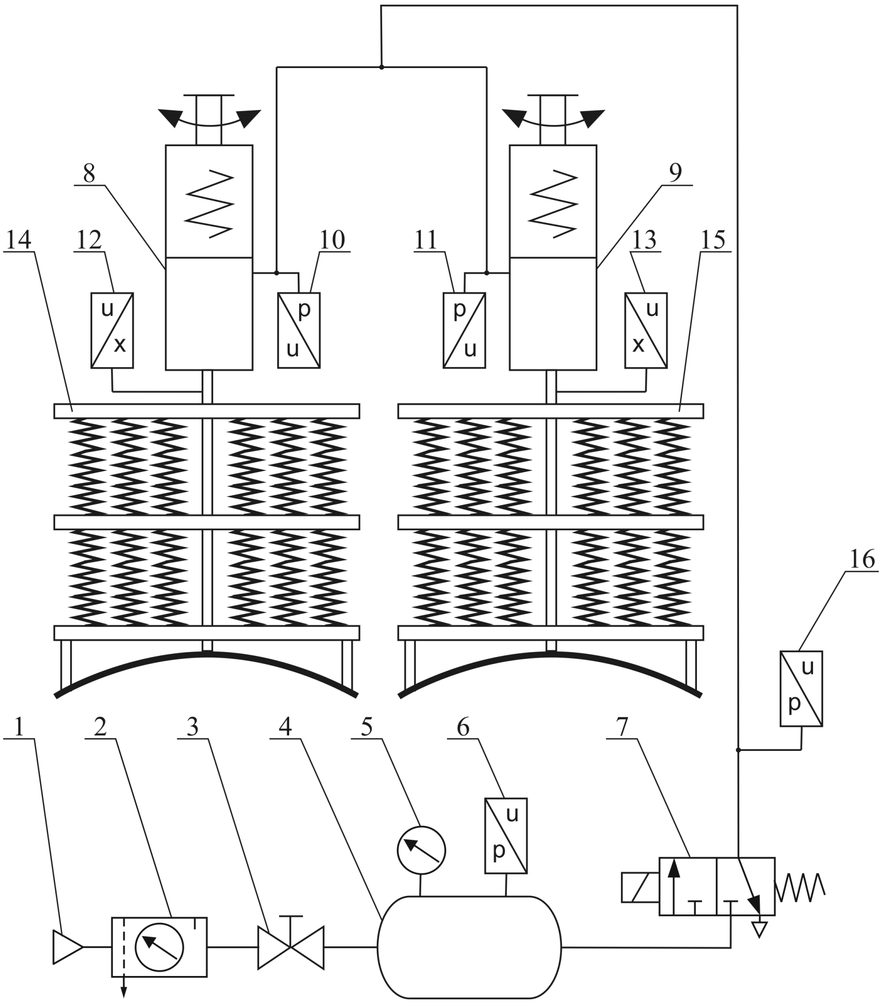

Fig. 4. **Diagram of laboratory station:** 1 **–** source of compressed air; 2 – compressed air preparation block; 3 – cut-off valve; 4 – compressed air tank with capacity 40; 5 – pressure gauge; 6 – pressure transducer in tank; 7 – pneumatic three-way dual-position electromagnetically-controlled valve; 8 – left membrane spring-loaded cylinder; 9 – right membrane spring-loaded cylinder; 10 – pressure transducer of left cylinder; 11 – pressure transducer of right cylinder; 12 – piston displacement transducer of left cylinder; 13 – piston displacement transducer of right cylinder; 14 – left characteristic change mechanism; 15 – right characteristic change mechanism; 16 – pressure transducer on valve

Results and discussion

Tests were based on braking and brake release of the pneumatic cylinder. Air pressure in the brake system was equal to 700 kPa during the conducted measurements. Time histories of compressed air pressure and piston rod displacements were registered.

Fig. 5 presents example results of measurements for two spring configurations of the loading mechanism.

a)
b)

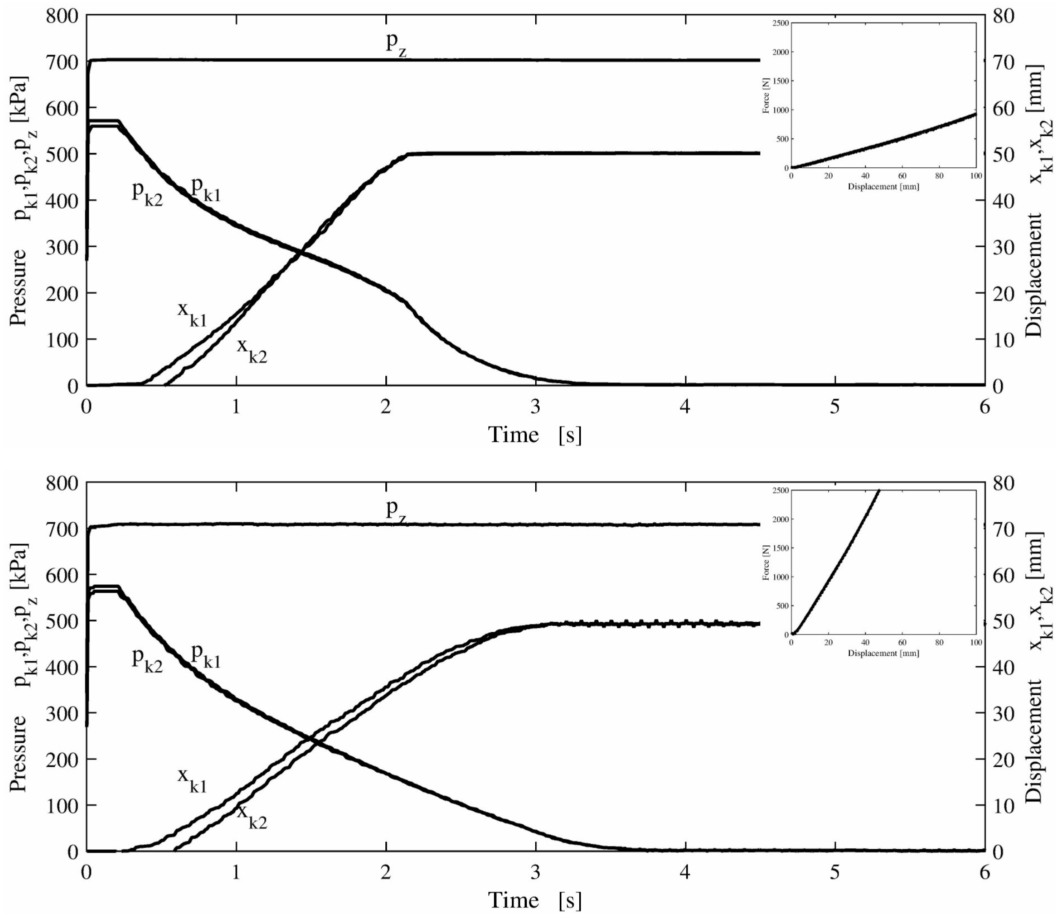

Fig. 5. **Dynamic braking characteristics for given cylinder load characteristics**

It can be seen in Fig. 5 that due to the symmetry of the tested pneumatic system the registered pressure p_{k1}, p_{k2} and piston displacement x_{k1}, x_{k2} changes are almost the same for both cylinders (i.e. p_{k1} changes in a similar way as p_{k2}, and x_{k1} – in a similar way as x_{k2}). The load characteristics of the cylinder piston have a noticeable impact on the time histories of air pressure in cylinder chambers, and consequently on the time histories of piston displacements. When the loading force increases gently (Fig. 5a), the pressure reduces quickly with noticeable humps, and pistons move fast (within approximately 2 seconds). As a result the vehicle will be stopped rapidly. When the loading force is steeper (Fig. 5b), the pressure reduces slowly, and pistons move slower (within approximately 3 seconds). Then, the vehicle will be stopped slower.

The experimental results obtained in the forms of the plots presented in Fig. 5 can be used to evaluate the mathematical model of the braking system. The model will be developed in the next stage of the research analysis of the presented braking system. The model will be used to simulate dynamic processes in the braking system for various geometrical and physical parameters of the system, e.g., for various lengths and diameters of the connecting tubes, volumes of cylinder chambers, spring stiffness coefficients. This way, the expected braking efficiency of the designed braking system can be evaluated already at its early design stage. Thus, the unknown parameters of the braking system (tube lengths and diameters, chamber volumes, spring stiffnesses etc.) ensuring the required performance of the system can be simply obtained by conducting computer simulations based on the developed model.

The reliability of the model will be provided by its experimental evaluation. Experimental results that can be used for such evaluation have been obtained in the present paper.

Conclusions

1. The objective of the conducted tests was to determine the effect of the load conditions in a membrane, spring-loaded brake cylinder on the dynamic characteristics of a pneumatic drive system, and thus, on time histories of the braking process. Fig. 5 shows that a change of the load characteristic of membrane cylinders affects the rate of discharge from the chambers of membrane spring-loaded cylinders, and thus, the withdrawal rate of cylinder pistons. Cylinder pistons withdraw within approximately 2 seconds in the case of a gently sloping load characteristic and within approximately 3 seconds in the case of a steep load characteristic. Braking time also changes depending on the rod withdrawal time, which directly affects the vehicle safety.
2. This article presents selected results of measurements, obtained for relatively short supply conduits of large diameter. At greater conduit lengths, as applied in the brake systems of heavy vehicles and trailers, an even greater increase of piston withdrawal time is observed as a result of the changing load characteristic of the cylinders.
3. Further research shall encompass the development of a mathematical model to calculate time histories of compressed air pressure and displacement of cylinder pistons under variable load conditions. This model will be verified experimentally on the basis of the obtained results of measurements and will serve as an aid for designing pneumatic brake systems for vehicles.

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