METHODS FOR IMPROVING THE DYNAMIC PROPERTIES OF THE AIR BRAKING SYSTEMS OF LOW-SPEED AGRICULTURAL TRAILERS

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Abstract

Too low an operating speed of trailer air braking systems may lead to an inhibition of the braking asynchrony of agricultural tractor trailer units. Improved braking dynamics advanced braking systems with an electronic control unit (e.g. Trailer EBS) provide a more rational solution for high speed agricultural vehicles. In this paper, an overview of other methods for developing the dynamic properties of air braking systems for agricultural trailers is described. This paper provides examples of braking system design parameters optimization, using a variety of accelerating valves and dynamic properties correcting devices, as well as, by using simple systems with an electronic controllers. The described methods of dynamic properties improvements can be used to improve the speed and operation synchrony of the air braking systems of low-speed agricultural trailers. The paper presents the influence of some of the described methods, with different levels of complexity, on the properties of typical air braking systems.

Keywords: air braking systems dynamic, agricultural trailer, braking system optimization, air brake valve

1. Introduction

In many EU countries, farm trailers and towed machines with air brake systems supplied and controlled by the tractor's pneumatic systems are used. Combined farm tractor pneumatic systems being currently in use, which enable operation with both single- and dual-line trailer braking systems, differ mainly in the type of the trailer brake control valve [29]. This valve can be actuated either mechanically, hydraulically or pneumatically, depending on the brake operating system used to actuate the tractor service brakes.

Vehicle braking systems face very high demands [5] for their dynamic and static properties. High-speed action during rapid braking (the response time less than or equal to 0.6 s) and tracking operation in slow braking are required. By tracking operation we mean a system's

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ability to maintain the proportional relationship between the input signal change (e.g. the pressure in the air brake chamber) and the output signal change (e.g. the movement of the brake pedal, the pressure in the control line) under steady state conditions. The tracking operation is achieved via a negative feedback inside the brake valves.

The course of transition processes in the tractor and trailer brake system, and especially the pressure variations in individual circuits or in the air brake chamber, have a significant effect on the braking force distribution and braking performance (the stopping distance, the braking ratio). A hysteresis effect which occurs in air brake systems may easily lead to serious traffic accident in an emergency braking condition [8]. For example, when a vehicle runs at speed of approximately 70 km/h, if the braking time is delayed 0.5 s, the braking distance will increase by nearly 10 m. This delay could lead to heavy longitudinal loads along the vehicle instantaneously [25]. The consequences can be more serious for the multi-axle trailers due to their larger inertia.

Experimental and simulation studies of agricultural vehicles that were carried out [9] showed small response time values in pneumatic tractor systems (the compact design) and large response time values in trailer air brake systems, often exceeding the limit value. The asynchrony of operation of tractor and trailer braking systems in the transition process (non-simultaneity of pressure changes in individual circuits) can affect the braking process just as differences in the pressure threshold do. From research [28] it is known, that even small differences in threshold pressures (the brake pressure at which the brakes just begin to operate) between the towing and the towed vehicles, which are well within the limits currently set by legislation, may cause rapid lining wear, an imbalance and a drop in braking performance. For this reason, trailer braking systems use relay emergency valves with an predominance device [6], [11], [29], which is able to produce a positive pressure at the valve outlet port, being adjustable in the range from 0 to approximately 1 bar. This device is used to compensate for any threshold pressure losses through the trailer braking system and to ensure an equal pressure in the control line and in the brake actuators. However, the relay emergency valve with the advance device cannot ensure the braking compatibility between the tractor and the trailer under unsteady states.

In commercial heavy vehicles, a significant improvement in the dynamic properties of air brake systems has been achieved through the use of electronic control [18], [19], [27], [34].

Some electronic systems for tractors and agricultural trailers are also being developed, for example in works TEBS G2.1 (Trailer Electronically (Controlled) Brake System) by KNORR-BREMSE [11], complete with ABS (Anti-lock Brake System), RSP (Roll Stability Program), EBS (Electrical Brake System) modules. Anti-lock braking system (ABS) is an electronically controlled system designed to control vehicle's steering and stabilise the vehicle during rapid emergency braking to prevent the wheel from locking [2]. In study [33], a new modelling and simulation methodology for a pneumatic brake system with ABS was developed, which is widely used in commercial vehicle. Work is also being carried out [7], [17], [21], on improving the algorithms for controlling ABS systems. At work [20] structure of ABS relay valve and its work theory were analysed. This article provides reliable theory for improving the performance and efficiency of anti-lock braking system of vehicles. Implementation of the electronic brake control technology in agricultural vehicles faces a number of difficulties.

Currently, electronic brake systems (EBSs), electronic brake force distribution (EBD) have been successfully applied mainly in the passenger cars, while the applications on multi-axle heavy vehicles (MHVs) are still relatively narrow and immature [35].

At work [10] an electro-pneumatic proportional valve was proposed to replace the ABS (Anti-lock Brake System) so as to control the brake pressure more accurately, but the reason why it has been rarely used in vehicles is their high cost. According to the CEMA position [4], the development of ABS systems for tractors is still in an early phase, insufficient to address the most important challenges in the braking of agricultural vehicles, such as the optimization of the overall braking performance of the tractor-trailer combination and the prevention of jack-knifing. Electronic braking systems must also be fully compatible with agricultural field applications without causing any additional risk under typical off-road working conditions.

According to CEMA [4], advanced electronic braking systems are a rational solution for high speed agricultural vehicles, especially for speeds above 60 km/h. For slow moving vehicles that travel at a speed of less than 40 km/h, the best way to improve the dynamic properties of their braking systems is by using conventional methods. This paper describes various methods of shaping the dynamic properties of agricultural trailer air braking systems, including the optimization of their design parameters, the use of different brake valves with dynamic properties correcting devices, as well as the use of simple systems with an electronic controller. The paper also presents examples of experimental and simulation results of selected methods for improving the dynamic properties of air brake systems.

2. Classification of methods and techniques to improve the dynamic properties of agricultural trailer air braking systems

The methods of increasing the speed of operation of braking systems can be ranked in the order of application from the simplest to the most complex ones [9], [16]:

- selecting the optimum parameters of pneumatic elements,
- using relay (accelerator) valves in the control circuit or the brake actuating circuit and making a rational choice of the valve location in the circuit,
- using a correcting device in the form of a differential valve in the brake actuating circuit, positioned in series after the relay emergency valve,
- ensuring a rapid opening of the relay emergency valve and maintaining it in the maximum opening position during sudden braking (in the transition process), which is achieved by:
    - using a correcting device with inertial negative feedback or with positive flexible feedback (modification of the relay emergency valve)
    - using a parallel pneumatic differential valve in the supply, control or actuating circuit,
    - using a parallel electro-pneumatic differential circuit.
- using a parallel electro-pneumatic control circuit with an electronic control unit to directly fill the brake cylinders with compressed air.

The term "correction" is to be understood as using additional equipment to change the structure and improve the dynamic properties of the braking system. Corrective devices should be used when the required speed of action of the circuit could not be achieved by optimizing the design parameters of the braking system. An advantage of the majority of corrective devices is that they do not significantly add to the complexity of the design and allow the speed of action of the existing system to be significantly increased without deteriorating its static characteristics and, as a consequence, the tracking action. The operation of correction devices, unlike accelerator valves, manifests itself only in the transition mode. In terms of their connection to the system, correction devices are classified into parallel and serial devices, and the devices with local feedback. Most often, as corrective devices, typical dynamic units are used, such as: an aperiodic unit of the first order, or an integrating or differentiating unit.

2.1. Selection of the optimum parameters of pneumatic components

The selection of the optimum cross-section of connecting lines, valves and connection elements, which put up resistance to the flow of air, is the first and foremost method of reducing the response time of the braking system. Therefore, it should be repeated in the design process after each change to the system configuration. The response time of valves as well as the long pipeline length have a direct impact for the performance of the pneumatic brake system, which translates into their control accuracy [3].

The study [23] is focusing on the mathematical model of a pneumatic brake circuit. Such model can be used at the design stage to optimize the parameters of pneumatic components. It is also worth adding, that in the process of modelling, the pneumatic elements are substituted with idealized elements in the form of lumped volumes and resistances [12].

Papers [1], [12], [14] describes the modelling of braking system by simplifying the valves and the actuators. Authors in work [22] developed a hybrid dynamical model to predict the pressure response of the relay valve. Other work [26] deals with the modelling of a typical heavy commercial vehicle along with the entire pneumatic brake system layout with actuating valves, control valves and foundation brakes to predict its dynamic behaviour and stopping distance. Authors confirm that the simulated stopping distance matches with the experimental results.

In [31] it was proven by experiment that a pipe in a pneumatic brake system accounts for 30% of the overall time delay by experiment. Therefore, the time delay caused by a pipe is an important part of the delay of a pneumatic brake circuit [32].

The results of simulation studies to determine the response time of a Pronar T654 [24] agricultural trailer's braking system for different inner diameters of pneumatic lines are shown in Fig. 1. The studies have shown that the highest speed of operation of the trailer's pneumatic braking system is obtained for a control line inner diameter of d=12 mm (a response time of t_r=0.369 s). The optimum value of the inner diameter of the transfer line is d=13 mm (t_r=0.371 s). The simultaneous adoption of the optimal diameters of the two lines results in a response time of t_r=0.361 s, which is shorter by 0.012 s than the time specified for the basic system. Shortening the response time, even by several thousandths of a second, is particularly important when it exceeds the limit values specified in the homologation regulations.

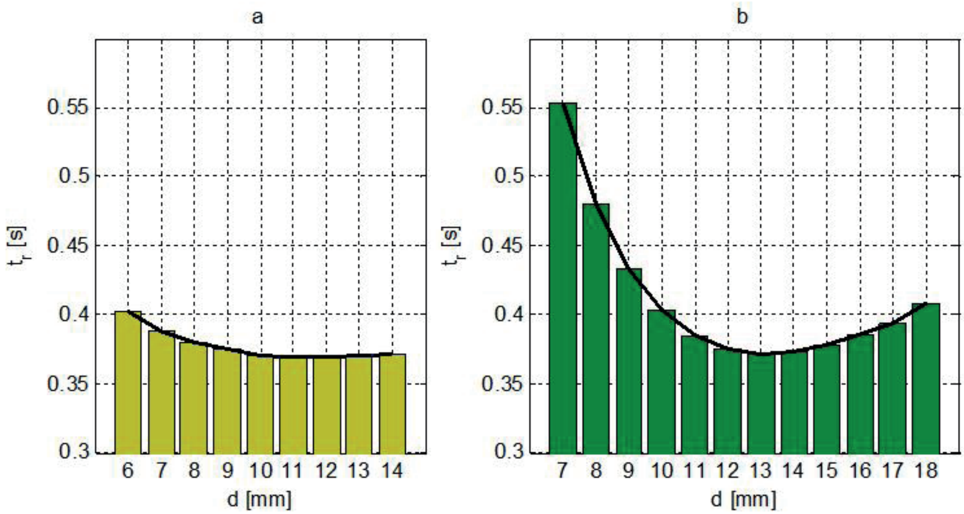

Fig. 1. The effect of the line inner diameter on the pneumatic braking system response time: a) control line, b) transfer hose [9]

The relationships between the pneumatic braking system response time and the control and transfer circuit line diameters, which show a distinct minimum, as illustrated in Figure 1, should be considered typical. Usually, increasing the cross-section (valve or line diameter) up to a specific value leads to an increase in system action speed.

However, an excessive increase in the cross-section increases the volumes of the elements, thereby increasing their pneumatic capacity. The duration of the volume filling (emptying) processes increases, and the action speed, instead of increasing, decreases. Moreover, the overall dimensions and masses of individual elements increase and the demand for compressed air increases, too. In multi-circuit systems, the choice of the rational flow capacity of lines and valves is difficult, because the dynamic characteristics of individual components should be adjusted to the dynamic properties of elements combined with them and interacting with each other. In branched circuits, that occur in multi-axle trailers, the proper connection of lines and pipe tees is also important – a circuit containing the cylinders of the farthest axis should be connected to the stub line (straight ahead), not to the bypass stub, as this reduces the reaction time by about 0.03 ÷ 0.04 s.

2.2. Using a pneumatic accelerating valve in the transfer circuit

An example of schematic diagram of a trailer's pneumatic braking system with a proportional accelerating valve is shown in Fig. 2.

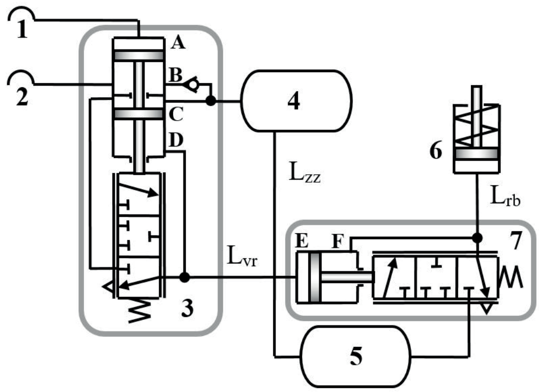

Fig. 2. Schematic diagram of a trailer`s pneumatic braking system with a proportional accelerating valve (relay valve): 1, 2 – control and supply circuits; 3 – trailer relay emergency valve; 4, 5 – reservoir; 6 – cylinder; 7 – relay valve; A÷H – valves chambers

Relay valve 7 (pneumatic proportional accelerating valve) should be used when, despite of the selection of the optimal cross-section of connecting lines and emergency trailer relay valve 3, the required response time of the system cannot be achieved. The tracking action of valve 7 is performed with the loop of rigid negative feedback (connection of the valve outlet to the cylinders with chamber F). Whereas, a significant shortening of the response time is achieved by installing a relay valve, together with additional reservoir 5 that supplies it, near the axis being braked.

The results of experimental studies indicate that installing a relay valve reduces the response time of the Pronar T654 trailer with the transfer circuit extended to 6.5 m by more than 15%. This response time can be further reduced through the optimal positioning of the accelerating valve, as shown by the results of simulation experiments. The studies involved the starting of the simulation process for different line lengths, L_{vr} and L_{rb}, upstream and downstream the relay valve (Fig. 3), being changed with a step of 0.25 m, while maintaining their total length of 6.5 m. Based on the time diagrams of pressure in the brake cylinder, the response time t_r to achieve 75% of the asymptotic pressure was determined. The length L_{zz} of the line connecting reservoirs 4 and 5 was varied by assuming $L_{zz}=L_{vr}$. The obtained results of verification of the response time tr for 9 sets of line lengths are shown in Figure 3. The shortest response time t_r = 0.315 was obtained for set no. 6, when the L_{vr} = 5.25 m, while L_{rb} = 1.25 m.

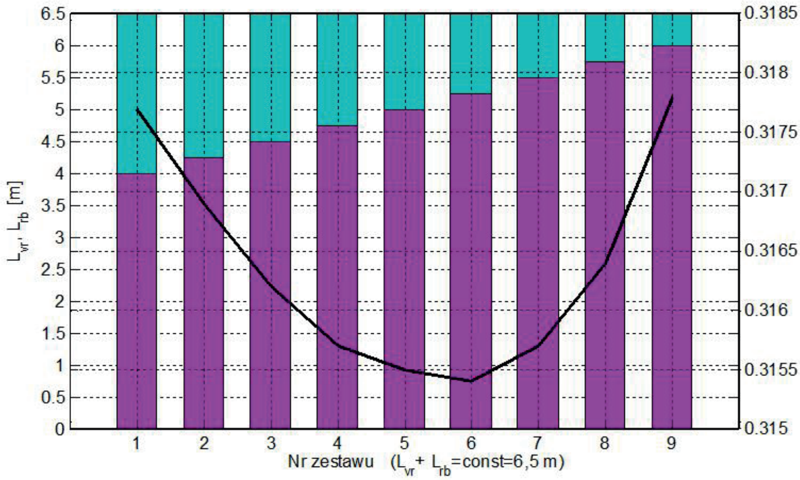

Fig. 3. The effect of line length on the response time of the braking system of the Pronar T654 trailer with the relay valve. [9]

This study and other studies [14] suggest that it is not always advantageous to place the accelerating valve immediately by the regulating unit (as is the case with the quick release valve), as the point is to shorten the time of both filling and emptying the regulating unit chamber. The optimal positioning of the accelerating valve depends on the specific drive system, and, in particular, on the total length of transfer and supply lines and on the regulating unit chamber volume.

The use of relay valves is a rational solution in the braking systems in multi-axle trailers with long transfer circuits, because it allows the standardization of the relay emergency valve construction in a series of vehicles; the main valve performs only the function of controlling the accelerating valves installed in the circuits of individual axles. A disadvantage of using the accelerating valves is an in-creased number of pneumatic components (increased costs) and a deterioration of the resultant static characteristics and tracking operation of the braking system. Therefore, when designing or selecting accelerating valves, special attention should be paid to both the conductivity and the dead zone of the valve, which should be as low as possible.

2.3. Using a correcting device in the form of a differential valve positioned in series after the relay emergency valve in the brake actuating circuit

Positioned in series in the transfer circuit, differential valve 8 (Fig. 4) does not have a negative feedback loop and is used for shortening the time of pressure build-up in the brake cylinder chamber only in case of a sudden overload of valve 3.

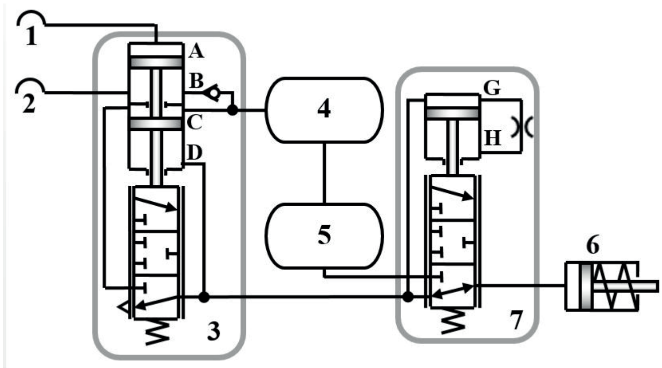

Fig. 4. Schematic diagram of a trailer`s pneumatic braking system with a differential valve; 1, 2 – control and supply circuits; 3 – trailer relay emergency valve; 4, 5 – reservoir; 6 – cylinder; 7 – relay valve; 8 – differential valve; A÷H – valves chambers [15], [16]

If the overdrive of this valve is slow, differential valve 8 does not operate, because the pressure in chambers G and H is equalized. Thereby, the proportional action of valve 3 is maintained. In the event of a sudden increase in pressure downstream valve 3, the differential pressure in valve 8 chambers G and H, connected by the throttle valve, causes an overdrive of the valve, allowing the air to flow from tank 5 to brake cylinder 6, until the pressure in chambers G and H equalizes. In transitional states, the dynamic characteristics of valve 8 is close to the characteristics of the differentiating unit with a delay. The differential valve can be built by modifying the ordinary relay valve, while its parameters, such as the volume of chambers G and H and the flow capacity of the throttle valve, should be assumed after making dynamic calculations at a varying input function increment rate. Due to the series connection of the corrective device, the rate of pressure build-up to a maximum limiting level changes only in the line section between corrective device 8 and regulating unit 6.

2.4. Using a modified relay emergency valve with flexible (inertial) negative feedback or with flexible positive feedback

A structural analysis made using the transmittance shows that it is possible to change the structure of the tracking device, which is the relay emergency valve, and make it an accelerating device by introducing an inertia into the negative feedback circuit (Fig. 5a) or by using an additional flexible positive feedback (Fig. 5b) next to the rigid negative feedback. The negative tracking action is called rigid, if its effect manifests itself both in the transient process and in the steady process. In contrast to the rigid feedback, the flexible feedback operates only in the transient states of device operation, while in steady states its operation fades out. The magnitude of the flexible feedback signal depends on the device output signal variation rate. Thus, the valves shown in Fig. 5 significantly shorten the braking system response time for step functions, while maintaining the proportional operation for slow variable input functions. Increasing the speed in the transient process is achieved at the expense of the full opening of the valve and keeping it in this position for some time, till the action of the correcting device disappears.

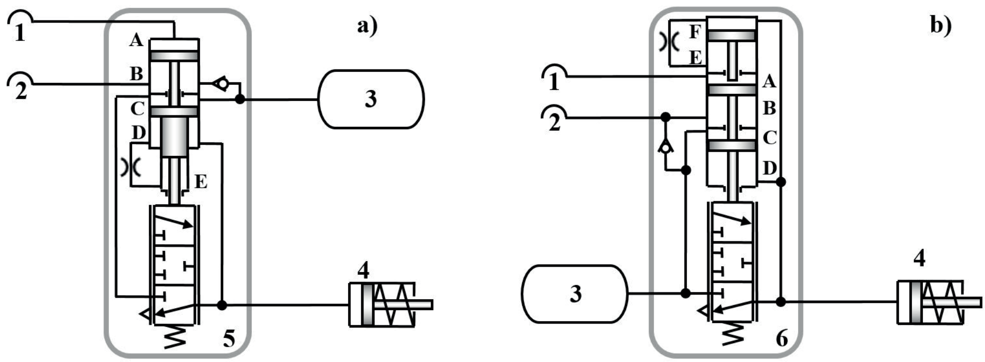

Fig. 5. Schematic diagram of the trailer braking system with a modified relay emergency valve: a) with inertial (flexible) negative feedback, b) with flexible positive feedback; 1, 2 – control and supply circuits; 3 – reservoir; 4 – cylinder; 5, 6 - relay emergency valve [15], [16]

In valve 5, Fig. 5a, besides the negative rigid feedback loop, also inertial negative flexible feedback occurs, which is accomplished by connecting the chambers D and E of the differential tracking piston with a needle valve. After a pressure has appeared in control chamber A, the pressure in output chamber D rapidly increases and may exceed the rate of pressure build-up in chamber A due to the fact that the pressure increase in chamber E being filled through the gland takes place with a delay. In steady states, i.e., with a slow increase in the control signal, the pressure in chambers D and E equalizes, which provides the tracking action – the air pressure in chamber D, thus also in the actuators, changes in so far as does the control pressure in chamber A.

The flexible (inertial) negative feedback has been obtained by using a so-called correction device in the brake valve Wabco 971 002 700 0 [29], that acts as a needle valve, with the possibility of adjusting the air flow area. The results of experimental studies to determine the response time t_r of a dual line 2 axle drawbar trailer's braking system for different correction device settings ($ZM_{D1},\dots, ZM_{D12}$) in comparison to factory valve extreme predominance value settings (ZF_{MIN}, ZF_{MAX}) shown on Fig. 6.

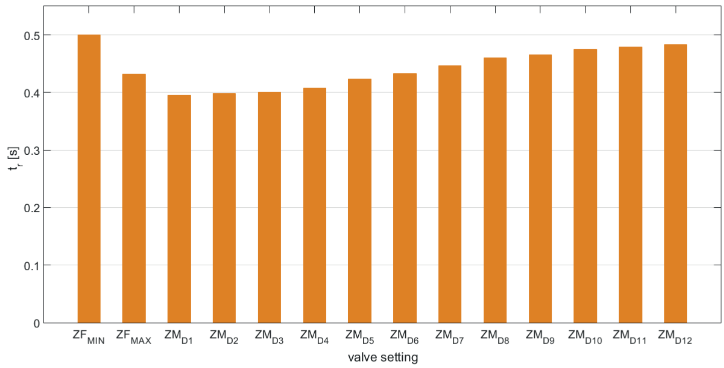

Fig. 6. The effect of the change in the air flow area of the correction device on 2 axle drawbar trailer braking system's response time t_r [s]

Setting the maximum pressure predominance value in the factory valve ZF_{MAX} (1 bar) reduces the response time by 11.5% for the rear axle system, compared to the response times of the braking system with valve a factory set of inactive predominance ZF_{MIN} (0 bar). In contrast, the use of a modified valve (with inertial negative feedback) with ZM_{D1} correction device setting reduces a response time by 18.8% for the rear axle of the trailer. By applying a correction device in valve, the required reaction time was obtained, less than 0.4 s, when with the standard valve braking system do not meet required value of reaction time.

The positive flexible feedback in valve 6 (Fig. 5b) is obtained using an additional piston, chambers E and F are connected together through the throttle valve. The full opening of valve 6 during fast transient processes is possible due to the fact that the output pressure (in chamber D) can increase more intensively than the pressure in control chamber A, which results in an increase in system operation speed. After the pressure in chambers E and F has equalized, the positive feedback action disappears and the tracking operation is resumed – the pressure at the outlet (in chamber D) varies in proportion to the pressure changes at the input (in chamber A).

The use of the above mentioned valves is recommended for trailers with extended control circuits. Valve 5 has a simple construction, which can be achieved by modifying the trailer braking valve equipped with a differential control piston. Instead of the differential pressure valve, a throttle valve must be installed to control the advanced action. Whereas, valve 6 can be easily built by modifying the serial trailer braking valves. Installing an additional piston in valve 6 slightly complicates its structure, but does not affect the durability and reliability of the valve.

A failure of the flexible positive feedback does not result in a failure of the drive system, but only reduces its operation speed. The throttle valves that determine the equalization of pressure in chambers D and E, and E and F are selected based on the dynamic characteristics of drive components, obtained e.g. from simulation tests.

2.5. Using a parallel differential correction circuit with a pneumatic or electro-pneumatic valve

The concept of parallel correction system is understood as an additional correction circuit, which is connected in parallel into the brake operating system. A signal from the control circuit is fed onto the input of both the operating and the correction system. The parallel correction circuit, in contrast to the series system, does not burden the main drive system and produces its own operation signal. The operation of the parallel correction system, similarly as the series system, manifests itself only in transient states, and therefore using this system only changes the dynamic properties of the follow-up circuit.

A long connection control circuit yields a longer duration of pressure changes in the chambers of brake valve 3 (Figure 7), namely in control chamber A and in output chamber D, which are connected to brake cylinders 5. To reduce that duration, and thus to increase the valve action speed, differential valve 6 is used in the supply circuit (Fig. 7a) or differential valve 7 (Fig. 7b) in the control circuit, which provide an additional element acting on valve 3.

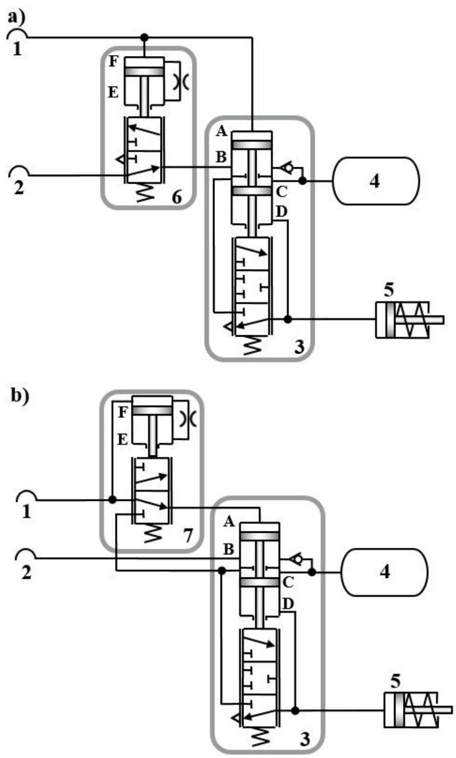

Fig. 7. Schematic diagram of the trailer pneumatic braking system with pneumatic differential valves: a) inverse differential valve 6 located in the supply circuit, b) proportional differential valve 7 located in the control circuit; 1, 2 – control and supply circuits, 3 – trailer relay emergency valve, 4 – reservoir, 5 – cylinder [15], [16]

As soon as the pressure starts to increase in control circuit 1and in connected with it chamber F, the differential device is actuated. Valve 6 (Fig. 7a) disconnects supply circuit 2 for some time and connects chamber B to the atmosphere. In fact, two signals act upon the valve: the signal to increase the pressure in chamber A and the signal to decrease the pressure in chamber B, with a fast proceeding transient process, which leads for some time to the full opening of valve 3, allowing a faster filling of the chamber of cylinder 5.

After valve 7 has actuated (Fig. 7b), the control chamber A of valve 3 is disconnected for some time from the control circuit, and connected to chamber C supplied from compressed air reservoir 4 until the pressures in the chambers E and F of valve 7 equalize.

The correcting devices under consideration are particularly effective in systems with a high resistance of the control circuit and the fully sufficient flow capacity of valve 3 and the transfer circuit. Installing correcting device 6 or 7 in the basic system does not require any modification to its construction and does not disturb its operation in steady states; yet it may considerably increase its operation speed. In the process of design using dynamic calculations, the flow capacity of the throttle valves connecting chambers E and F is determined, the best location of the differential valves is establishes, the optimum diameters in terms of operation speed is selected, and finally, the variant of differential valve connection diagram is assessed.

If the flow capacity of brake valve 3 and the transfer circuit lines is not sufficient to ensure the required operating speed, i.e. when there is a large delay in pressure variations in the actuator relative to the pressure in the control chamber A of valve 3, it is advisable to employ a parallel correction circuit with differential valve 6 to act directly upon brake cylinders 5 (Fig. 8a).

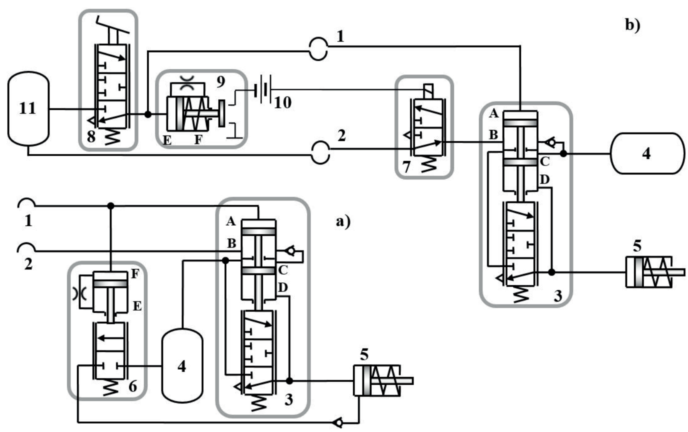

Fig. 8. Schematic diagram of the trailer pneumatic braking system: a) with a pneumatic parallel differential valve in the transfer circuit, b) with an electro-pneumatic correction circuit: 1, 2 – control and supply circuits; 3 – trailer relay emergency valve; 4, 11 – reservoirs; 5 – cylinder; 6 – pneumatic differential valve 2/2; 7 – electro-pneumatic valve 3/2; 8 – trailer relay emergency valve; 9 – differential cylinder; 10 – electrical circuit [15], [16]

With a sudden increase in pressure at the input of control circuit 1, a rapid increase in pressure in the chamber F of differential valve 6 follows. This causes the actuation of valve 6, whereby the compressed air quickly fills the working space of brake cylinder 5. The duration of maintaining valve 6 in the open state depends mainly on the magnitude of resistance connecting F and E, on the volume of E and on the stiffness of the return spring of differential valve 6.

An advantage of the parallel correction circuit is the possibility of using it as a complement to the basic drive without having to change its construction. A disadvantage may be the undesirable air flow from cylinders 5 to the atmosphere through valve 3, should valve 6 be actuated earlier than valve 3. In order to ensure the synchronous activation of both valves, and thus to eliminate the unnecessary air leak to the atmosphere, in the design process one should provide the identical flow capacity of the two parallel paths (via valve 3 and valve 6) of air flow from reservoir 4 to cylinder 5; select both valves with the identical dead zone; connect the chamber F of the differential valve directly to the control chamber A of valve 3, or to control circuit 1 in the vicinity of valve 3. In the latter case, the flow capacity of the line section from the place of branching to valve 6 should be greater than the flow capacity of the connection between the differential valve with control circuit 1.

A further design development of the parallel correction circuits is to use, in place of the differential pneumatic valve, its equivalent controlled electrically from the tractor. In the example shown in Fig. 8b, three-way electro-pneumatic diverter valve 7, supplied from circuit 2, is positioned near trailer relay emergency valve 3. Electric circuit 10 is used for connection to differential valve (cylinder) 9, which should be placed as close as possible to valve 8 that controls the trailer braking system from the towing vehicle. Chamber E is connected to the output of valve 8.

Parallel correction circuits with electro-pneumatic valves may be used with a considerable length of the control circuit, when the action of the differential pneumatic valves is insufficient [26]. In addition, they can significantly improve the synchrony of action of the braking system of tractor sets.

2.6. Using a parallel electro-pneumatic control circuit with an electronic control unit

Examples of dual-circuit trailer braking systems with correction circuits with electronic control unit and direct action upon the brake cylinders are shown in Figures 9 and 10. In addition to the typical pneumatic components, they include an EBS electronic control unit that generates signals controlling the switching the solenoid valves on and off based on the pressure value measured at different points in the braking system of the trailer or the towing vehicle.

In a simpler solution of the dual-circuit system (Fig. 9), electronic controller 11 generates signals that control solenoid valves 6, 7, 8 based on the value of pressure prevailing at the beginning of control circuit 1 (transducer 9) and in the chamber of brake cylinder 5 (the transducer 10). Switching valve 7 on and valve 8 off causes the compressed air to be supplied to the chambers of brake cylinders 5 directly from reservoir 4. Valve 6 is used to cut off the air flowing through circuit 1 to control valve 3, which, in the case of normal electronic control unit operation, is not involved in the braking process. In case of a failure or lack of the power supply of the electronic control unit, valves 6 and 7 are open and valve 8 is closed. In that case, the braking is controlled directly by valve 3. An increase in pressure in control line 1 causes a proportional pressure increase in brake cylinders 5, and the system operates as a normal dual-circuit pneumatic system.

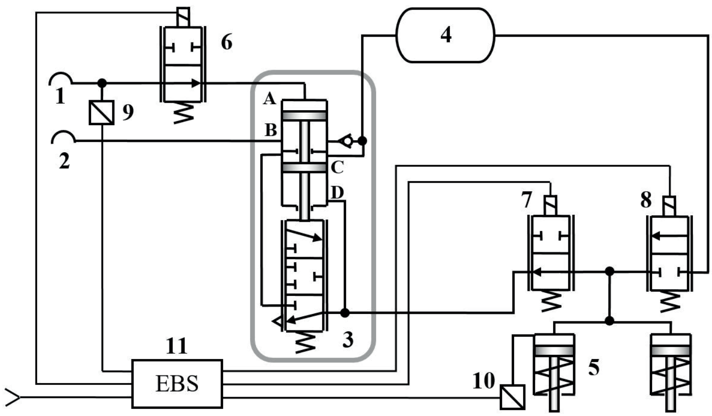

Fig. 9. Schematic diagram of the trailer dual-circuit pneumatic braking system with an EBS; 1, 2 – control and supply circuits; 3 – trailer relay emergency valve; 4 – reservoir; 5 – cylinder; 6, 7, 8 – pneumatic differential valve 2/2 (EPZ); 9, 10 – pressure transmitter; 11 – electronic control unit (EBS) [15]

During braking of the vehicle set, the braking system of which is shown in Figure 10, the compressed air from reservoir 17 of the towing vehicle, gets through relay emergency brake valve 16 to brake cylinders 18. As soon as the air pressure in the chambers of tractor cylinders 18 begins to rise, a discrepancy in signals forms at the inputs of electronic unit 15, which generates output signals, under the influence of which electro-pneumatic valves 9, 10 and 11 are overridden into the active position.

At the same time, only trailer front axle cylinders 6 are filled via valve 3, while cylinders 7 and 8 are filled through valves 10 and 11. As a result, the response time of all the trailer brakes is significantly reduced. After the pressure in all vehicle cylinders has equalized, the electric output signals in the EBS disappear, so valves 9, 10 and 11 pass into the initial position and the trailer braking system begins to operate as a normal pneumatic system. After completion of the braking, the compressed air from cylinders 7, 8 and 6 is discharged to the atmosphere through control valve 3.

In case of a failure of the electric circuit of power supply of valves 10 and 11, valve 9 will automatically return to the initial position and the control of braking of all the three trailer axles is effected by brake control valve 3. In a situation where the electronic unit is completely non-operational, the control of braking proceeds in a similar manner.

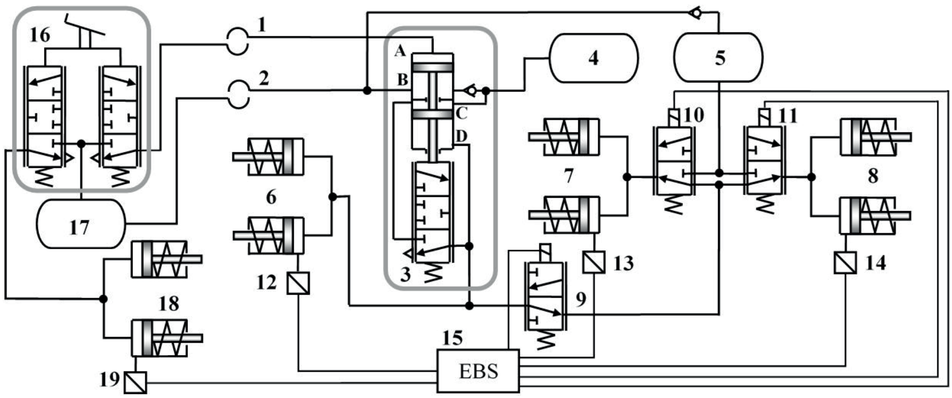

Fig. 10. Schematic diagram of the dual-circuit electro-pneumatic multi-axis trailer braking system with an electronic control unit: 1, 2 – control and supply circuits; 3 – trailer relay emergency valve; 4, 5,17 – reservoirs; 6, 7, 8 – front, central and real axle cylinders; 9, 10, 11 – electro-pneumatic valve 3/2; 12, 13, 14, 19 – pressure transmitters; 15 – electronic control unit (EBS); 16 – main braking valve; 18 – tractor cylinders [11], [15]

In [13] they were compared two commercial vehicles, one with a traditional treadle valve brake system and another with a 2 EPR brake system. The experiments proved a difference in average time lag being 400 ms and 125 ms respectively. Thus, under the same operating conditions, it was observed that the EPB system with two EPRs reduces the stopping distance by at least 6.11 m. Thus, the two EPR brake system leads to a faster response and a smaller stopping distance when compared with the traditional treadle valve air brake system.

The most important advantages of electro-pneumatic braking systems with electronic control include [30]:

- braking time is reduced through shorter response time and pressure build-up time of the brakes on the front and rear axle(s)
- improved braking stability by synchronized operation of the brake cylinders,
- reliability (in the case of a failure of the electronic system, braking is still possible)
- a longer operation time of the trailer relay emergency valve (it is only used in the event of a failure of the electronic system).

A disadvantage of this type of systems is the need for using additional control solenoid valves, pressure sensors and electronic control units. An electro-pneumatic proportional valve was proposed to replace the ABS, so as to control the brake pressure more accurately [10], but it has been rarely used in vehicles because of its high cost.

3. Summary

The optimization of the design parameters of the pneumatic components and the selection of the rational positioning of the relay valves are among the simplest and standard methods used in the process of designing agricultural trailer braking systems. Unfortunately, in many cases, their use does not give satisfactory results.

A more substantial improvement in the dynamic properties of trailer braking systems can be achieved by using various types of corrective devices. When choosing a particular solution, a number of factors should be taken into account, including:

- the effectiveness of corrective device operation in a specific braking system,
- the design complexity of the solution and its implementation in the braking system,
- the absence of the corrective devices' impact on braking system operation in steady and quasi-steady states,
- ensuring the reliability of braking system operation in case of a failure of the corrective device,
- the economic viability of the solution.

From among the described systems containing corrective devices, the systems shown in Fig. 5 and Fig. 6 can be recommended, because of the convenience of technical implementation in slow moving trailer brake systems. The correction devices occurring in these systems have a simple construction and can be built by modifying the existing brake valves. Moreover, installing them in a braking system does not require so many modifications to the system configuration, as when installing parallel differential valves. A modification of the braking valve, by introducing flexible (inertial) feedback, allows to meet the requirements for pneumatic braking systems (achieving the required response time).

Electro-pneumatic trailers braking systems with electronic controllers are characterized by a high complexity of their structure. Their implementation in agricultural vehicles is conditioned by the introduction of standardization in the control systems of farm tractor and trailer braking systems.

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