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SYNTHESIS OF PNEUMATIC SYSTEMS IN THE CONTROL OF THE TRANSPORT LINE OF ROLLING ELEMENTS

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Abstract: This paper presents the synthesis of a pneumatic control system for a selected configuration of the transport path for the delivery of rolling elements to spiral storage in inter-operational transport. The sequential control system sets the state of the manifolds to ensure a flow of workpieces to serve the subsequent storage. The essential module of the control system is the memory block. It is developed based on a storage filling sequence graph. The filling level of the storages can be monitored in one or two points using sensors. The rolling element displacement control sensors work together with appropriately designed systems to execute the delay of the rising and falling edge input signal. By using a two-level control of the filling level of the storages, it is possible to control the emptying status of the storages as a function of the technological time of removal of the items from the storage between the two control points. Control systems were synthesised and verified using Festo's FluidSim computer programme.

Key words: pneumatic systems, delay execution systems, synthesis, verification of sequential systems

1. INTRODUCTION

In high-volume production of rolling elements of all kinds, automation of the transport route between subsequent production stages is simply necessary. In this type of production, special machine tools with a high degree of automation are used to tool the components. Activities such as supplying components to workstations, applying products for machining, etc., result in increased worker utilisation, and these can be performed much more quickly by a unit of equipment configured in a mass handling system. The automation of the inter-operational transport route increases the productivity of machine tools almost to the maximum and reduces the costs associated with the transport of workpieces. The transport system must also be capable of being tuned, for example, to produce components of a different type, and thus it requires the control equipment to use universal modules that are independent of the transport path configuration.

There are many tasks involved in designing, among which one of the most significant is the analysis and synthesis of the schematic diagram of the device [1,2].

In sequential circuits [3], the current state of outputs depends not only on the current state of inputs but also on the sequence of previous input states, while in combinational circuits [4] the current state of the outputs depends only on the current state of the inputs.

In sequential asynchronous systems, the clock signal does not occur. The input signals directly affect the internal state of the system at all times. Thus, each input change causes an immediate (taking into account the signal propagation time through the system) reaction of the system [5].

The lack of a clock signal makes the synthesis of asynchronous circuits, in general, more difficult than the synthesis of synchronous circuits [6].

The synthesis of sequential circuits using the conventional method of transition and output tables is simple if the number of inputs and the number of internal states are not large. However, for systems with more than three inputs and eight internal states, the burden of using the transition and output tables increases significantly, the synthesis algorithms become more complicated (for example, the excitation functions then depend on seven arguments) and the chance of obtaining an optimal solution decreases [7].

In order to meet the expectations of system designers regarding the minimisation of the mathematical apparatus in the analysis of systems, an algorithmic approach to the synthesis of sequential systems was presented [8]. The programming language that has gained the greatest popularity among PLC programmers is the Ladder Diagram language [9]. The reason for this is that it is easy to understand due to its similarity to contact-relay diagrams [10]. Ladder logic also allows the user to perform more complex operations such as arithmetic and time operations. The control scheme in this language is in the form of symbols placed in circuits resembling the ladder of a relay scheme. This language allows the user to build control systems based on logical dependencies resulting from Boolean algebra [7].

The material presented in the article is a continuation of the research issues discussed in an earlier paper in the literature from the authors of the present study [8], in which the synthesis of the sequential electropneumatic system with the use of logical elements was presented, and discussed in other studies in the litera-

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ture from the same authors [11, 12], in which the problems of the synthesis of sequential electropneumatic systems were presented.

The control of the transport routes is carried out through distributors consisting of actuators working together with two-state valves [13,14].

In the case of continuous actuator position control systems, proportional valves are used [15,16], while digital position transducers [17] are used to measure actuator position, enabling precise actuator position control.

The literature [18,19] provides selected examples of control system design using pneumatic components and devices. In control systems, the positioning accuracy of actuator elements is of vital importance [20,21]. An analysis of accuracy in signal processing is presented in the literature [22,23].

The general configuration of the transport line for delivering rolling elements to the storages is shown in Fig. 1.

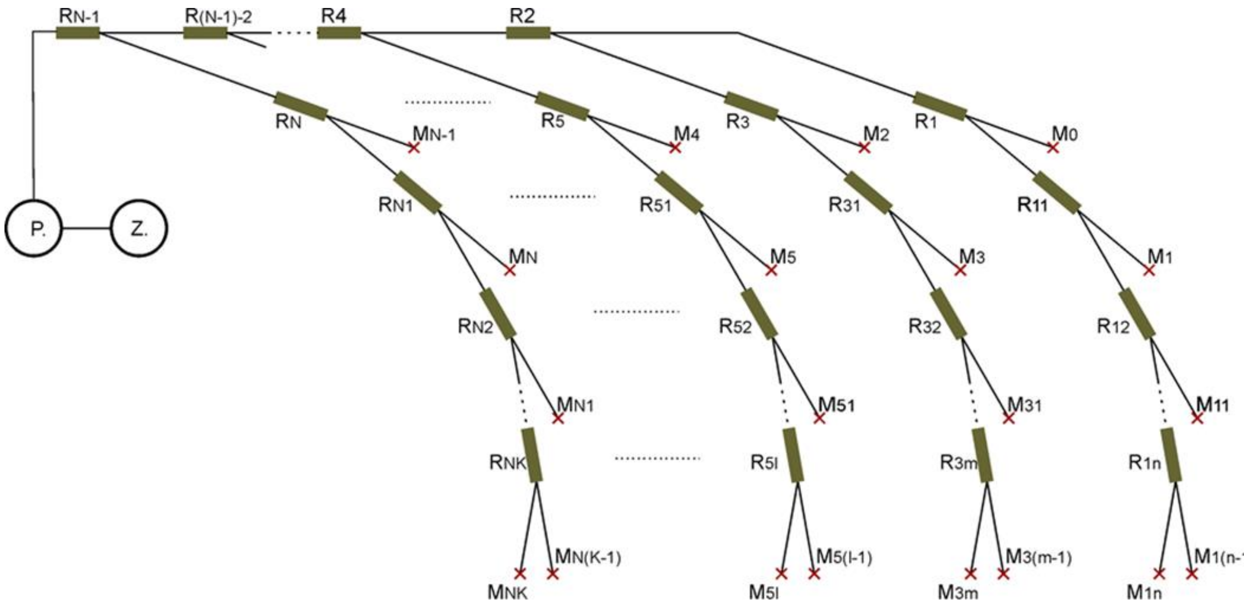

Fig. 1. Generalised configuration of the transport line section: Z – bin, P – vertical lift, R – distributors of transport routes, M – spiral storages

The transport line can be configured in any way by means of a suitable connection of the R distributors. The rolling elements are lifted from the Z bin to a certain height by means of the P vertical lift and directed via the R distributors to the corresponding M spiral storage using the force of gravity and the properties of the rolling elements.

In the general case, the number of M storages is greater than the number of R distributors by one, i.e. for R = X, M = X + 1.

This paper presents a method for the synthesis of an automatic control system for the distribution of rolling elements, using the example of a transport line section with M = 8 storages and R = 7 distributors. The configuration shown in Fig. 2 is an outtake of a generalised transport line section configuration.

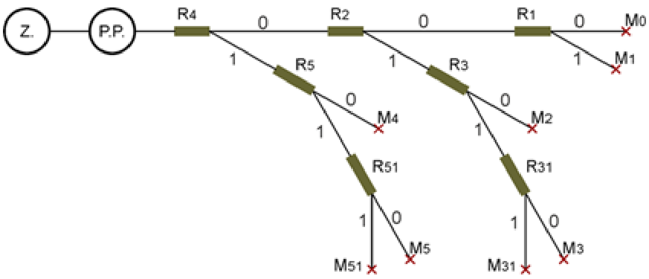

Fig. 2. Configuration of the analysed transport line M = 8, R = 7

The choice of transport route depends on the signals coming from the storage fill level sensors. Tab. 1 shows the status of setting up the R distributors to provide a flow of workpieces to the selected storage.

Tab. 1. The state of the R distributors to ensure the flow of workpieces to relevant M storages

	R1	R2	R3	R31	R4	R5	R51
M0	0	0	-	-	0	-	-
M1	1	0	-	-	0	-	-
M2	-	1	0	-	0	-	-
M3	-	1	1	0	0	-	-
M31	-	1	1	1	0	-	-
M4	-	-	-	-	1	0	-
M5	-	-	-	-	1	1	0
M51	-	-	-	-	1	1	1

For example, in order to provide flow to the M31 storage, distributors R2, R3 and R31 must be in state 1, i.e. on, and distributor R4 in state 0 (off), while the other distributors may be in any state.

The filling level of the storages can be monitored in one or two points using sensors. Sensors for the control of moving rolling elements must work in conjunction with appropriate delay execution systems.

This article presents the pneumatic measuring and control systems developed for use in the inter-operational transport of rolling elements. In pneumatic systems, divide valves, check and throttle valves and pneumatic capacities, among others, are used as input signal time delay systems [24]. Through various combinations of these elements, a delay in the appearance or disappearance of the output signal in relation to the input signal is obtained. By routing the input signal to the check and throttle valve, the

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output of which is connected to the pneumatic capacity and the valve control input, a delay in switching the valve on or off is achieved, depending on the direction in which the check and throttle valve is switched on. The time delays are selected by the parameters of pneumatic capacity and damping of the check and throttle valve. By connecting opposite-acting check and throttle valves in series, the output of which is connected to a pneumatic capacity and a valve control input, a delay in valve switching on and off is achieved, reflected by the delay in the appearance and disappearance of the output signal relative to the input signal. Transducer (time-dependent) systems built based on a series connection of check and throttle valves do not have the ability to control the duration of input signals with a set time in the case of input signal sequences with a duration less than the set time, which is a major drawback. The above drawback was eliminated by appropriately designed circuits for executing the delay of the rising and falling edge input signal, working in conjunction with sensors to control moving components. Pneumatic jet sensors are used as control sensors [25]. They work on the principle of sensing the reflected air stream from an aperture (in this case, a rolling element) or interruption of the air stream by a moving workpiece. The filling level of the storages can be monitored in one or two points using sensors. By using a two-level control of the filling level of the storages, it is possible to control the emptying status of the storages as a function of the technological time of removal of the items from the storage between the two control points.

The developed system is dedicated to applications with high requirements for reliable operation in adverse environments (dust, high temperature, magnetic field, etc.).

2. SINGLE-POINT SPIRAL STORAGE CONTROL SYSTEM FOR ROLLING ELEMENTS

Fig. 3 shows the system developed to work with a pneumatic sensor for single-point measurement of the fill level of a rolling element storage.

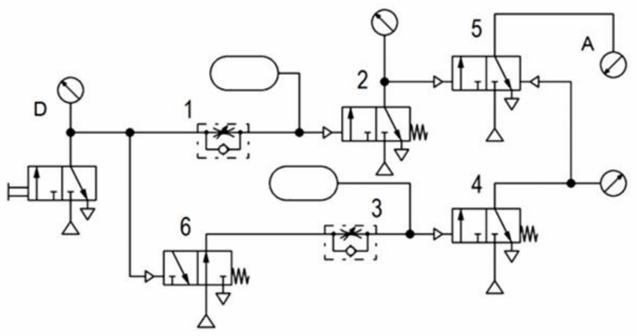

Fig. 3. Single-point storage state control system

The system was set up using diverter valves, throttle valves and pneumatic capacities. The delaying system diagram shows all these elements, regardless of whether they form a structural whole or are independent elements connected by wires. Through various combinations of these elements, a delay in the appearance or disappearance of the output signal in relation to the input signal was obtained. This is important, since moving rolling elements in the control sensor zone cause the generation of a brief pulse of change in the signal state of this sensor.

The system does not react to short pulses, shorter than the set delay time of the rising edge of the input signal (signal head), and shorter than the set delay time of the falling edge of the input signal (signal rear). The head delay of the D signal of the control sensor was obtained at the output of valve 2 of the system, while the rear delay of the signal D of the control sensor was obtained at the output of valve 4 of the system. The signal at the output of valve 2 causes output valve 5 to be switched on, generating an A signal at high level (logical 1) – that is, it reflects the state of the presence of rolling elements in the storage. The high state of the signal at valve output 4 switches off output valve 5, changing signal A to a low level (logical 0), reflecting the absence of rolling elements in the zone of the storage control sensor.

The cyclogram of the system operation is shown in Fig. 4, which explains the operation of the system in Fig. 3.

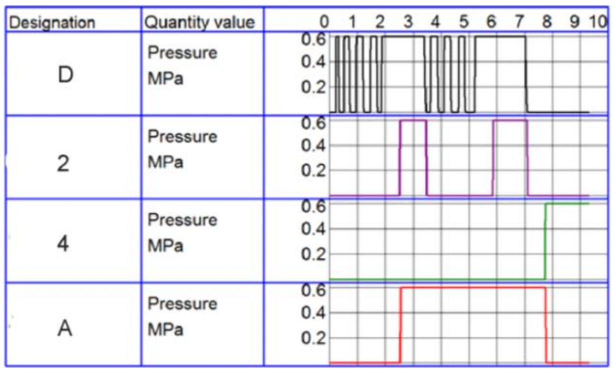

Fig. 4. Cyclogram of the operation of the single-point storage state control system

It should be emphasised that the rise and fall delay time of the input signal is selected in the process depending on the speed of movement of the components in the rolling element control sensor zone.

3. TWO-POINT SPIRAL STORAGE CONTROL SYSTEM FOR ROLLING ELEMENTS

Fig. 5 shows the developed system for controlling the fill level of the storage by means of two measuring sensors, i.e. sensor D for the lower position of the rings in the storage and sensor G for the upper position of the rings in the spiral storage. A rising and falling edge input delay system works with each sensor. These systems are identical to the systems discussed in item 2, and shown in Figs. 3 and 4.

The essence of the developed system consists in linking two sensors D and G cooperating with the head and rear delay systems of the input signal, with a corresponding memory system.

The arrangement of the combination of the two valves 7 and 8 and the sum element 8 constitute a memory system C, in which the output signal C reflects the state of the spiral storage. When the storage is unfilled, the output signal of the C memory system is in a low state (logic state 0). When the storage is filled to the lower D level, the output signal of the A delay system is in a high state (logic state 1), overdriving valve 8 by feeding the low level C output signal of the memory system to the 9 sum valve.

When the storage is filled to the upper G level, the output signal of the B delay system is in a high state, and it is fed to the 9 sum element of the memory system.

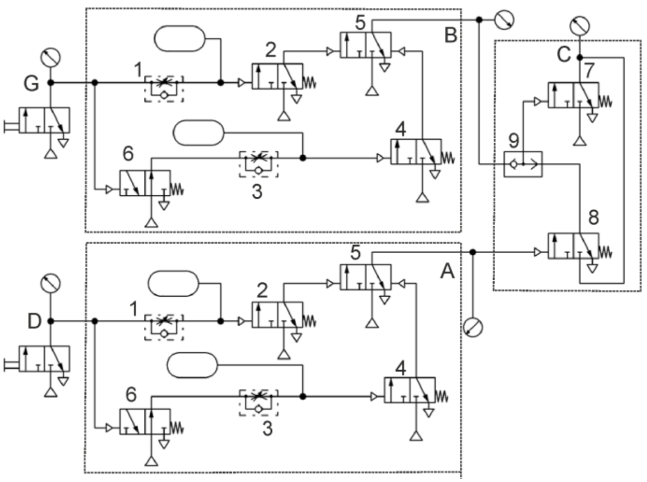

Fig. 5. Two-point spiral storage control system for rolling elements

This switches valve 7 and applies high pressure to output C of the memory system. This state is maintained by valve 8 controlled by signal A and 9 sum system, providing feedback to the memory system. When the storage is emptied in the process, the first step is to change the state of the upper G level sensor of the storage (the B-output signal of valve 5 changes from high to low). The state of the C signal of the memory chip is still high. Further emptying of the storage below the level of the lower storage D level sensor changes the signal of the delay system A to low and thus changes the state of valve 8 controlled by this signal.

There is then a change in the state of the memory system, thereby changing the C signal to a low state, which is signalled as a storage requirement for elements.

The exact operation of the designed system is illustrated by the cyclogram shown in Fig. 6.

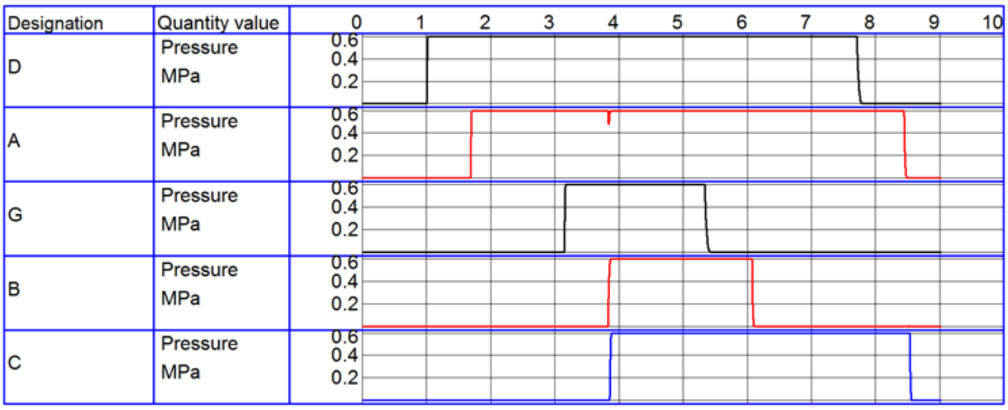

Fig. 6. Cyclogram of the operation of the double-point rolling element spiral storage state control system

It should be emphasised that the time between the change in state of signal B from high to low and the change in state of signal A from high to low is the storage delay time known as the technological process adaptation time.

4. MINIMISED TWO-POINT SPIRAL STORAGE CONTROL SYSTEM FOR ROLLING ELEMENTS

Fig. 7 shows the developed system for controlling the fill level of the storage by means of two measuring sensors, i.e. sensor D for the lower position of the rings in the storage and sensor G for the upper position of the rings in the spiral storage, which work with a single system for delaying the input signal of the rising and falling edge and the system implementing the logic function (¬D+A)¬G. The delay system for the rising and falling edge input signal is identical to the system discussed in item 2, which is shown in Fig. 3. The system implementing the logic function (¬D+A)¬G is set up using appropriately connected elements 7, 8, 9 and 10. The output of this system is connected to the input of the rising and falling edge delay system.

The exact operation of the designed minimised two-point spiral storage control system for rolling elements is illustrated by the cyclogram shown in Fig. 8.

It should be emphasised that in the systems in Figs. 3, 5 and 7, time delay valves, type VZ-3-PK-3 by Festo [24], were used. For the analysis of the developed systems, this valve was adopted because it meets the requirements of setting the time delay range (0.25–5.0 s).

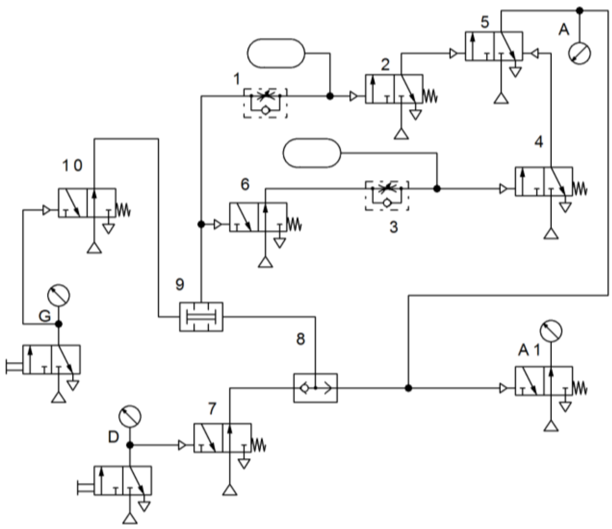

Fig. 7. Minimised two-point spiral storage control system for rolling elements

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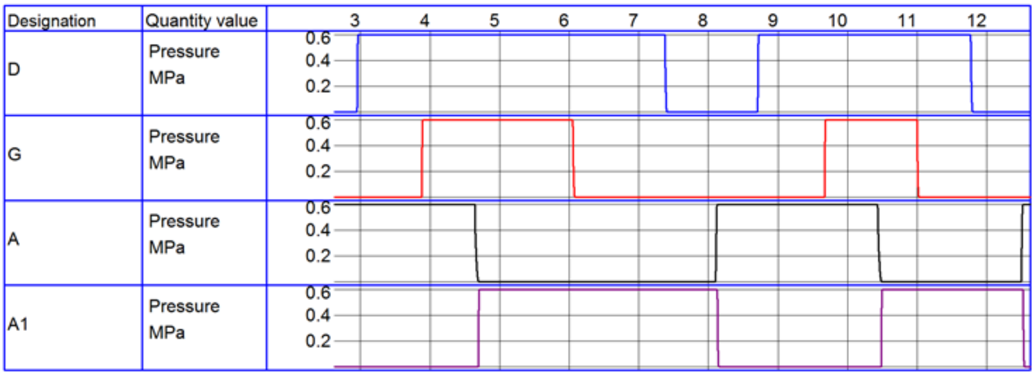

Fig. 8. Cyclogram of the operation of the two-point spiral storage control system for rolling elements

5. SYNTHESIS OF A CONTROL SYSTEM FOR THE SUPPLY OF ROLLING ELEMENTS TO A SPIRAL STORAGE

The essential module of the control system is the memory block. It is developed based on a storage filling sequence graph. In the graph, the order in which the storages are filled is assumed from M0 to M51, as shown in Fig. 9.

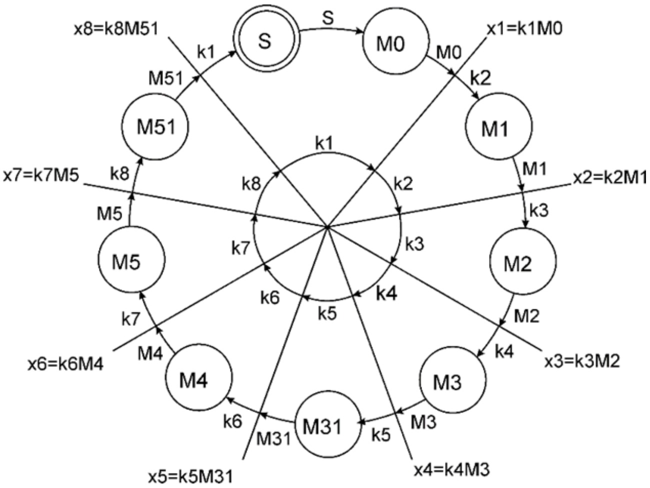

Fig. 9. Graph of storage filling sequence

The graph was divided radially by assigning a k memory state to the individual M storages. On the division line, the signals xn specifying the transition to the next state kn were defined (filling a storage in kn state allows the transition to filling the next unfilled storage).

The graph indicates the memory state that the sequential storage filling system is in when filling the detail storage. This is illustrated in Tab. 2. The memory is in a high state for the filled storage. The selection of the next storage is possible in the next memory high state (logical state 1), i.e. in the wandering memory high state.

Based on the graph (Fig. 9) and the status of the distributors, a sequential control system for filling the storages was developed to ensure the flow rate of the workpieces to the corresponding M storages (Tab. 1), as shown in Fig. 10.

The system consists of three main elements:

- M0–M51 single- or two-point storage filling control systems in accordance with Figs. 3, 5 or 7;
- memory system k1–k8; and
- control system for the flow divider elements R1–R51 for the storages M0–M51.

Tab. 2. Sequence of storage filling depending on memory status

	k1	k2	k3	k4	k5	k6	k7	k8
M0	1	0	0	0	0	0	0	0
M1	0	1	0	0	0	0	0	0
M2	0	0	1	0	0	0	0	0
M3	0	0	0	1	0	0	0	0
M31	0	0	0	0	1	0	0	0
M4	0	0	0	0	0	1	0	0
M5	0	0	0	0	0	0	1	0
M51	0	0	0	0	0	0	0	1

Pneumatic memory has been implemented on 4/2 valves (four-connection two-position valves) controlled by x1–x8 signals, with each subsequent memory state erasing the previous one. The status of the storages is reflected by the signals M0–M51 (the signals represent the status of the control sensors together with the delay systems). The state of the flow distributors is controlled by the sum elements as shown in Tab. 1. Distributors not involved in the flow setting for filling the currently selected storage are in the setting from the previous flow setting – it is uneconomical to overdrive them to the zero position. In addition to selecting successive memory states, the storage filling control system is responsible for switching the vertical feeder on or off and stopping the cycle in state k1, according to the relation S = k1 [(M0) + (M1) + (M2) + (M3) + (M31) + (M4) + (M5) + (M51)].

The system shown in Fig. 11 is undergoing simulation in the filling state of storage M5, with distributors R4 and R5 on (state 1 setting) and distributor R51 off (logic state 0), and in memory state k7.

Fig. 12 shows an example of a simulation cyclogram of a sequential control system for filling spiral storages for rolling elements. In the initial state, storages M1, M3, M31 and M4 are filled.

In the simulation presented, the following phases of the system should be distinguished:

- in the first instance, the rolling elements are delivered to the M0 storage, distributors R1, R2 and R4 are in the off state (logic state 0) and the vertical feeder is switched on;

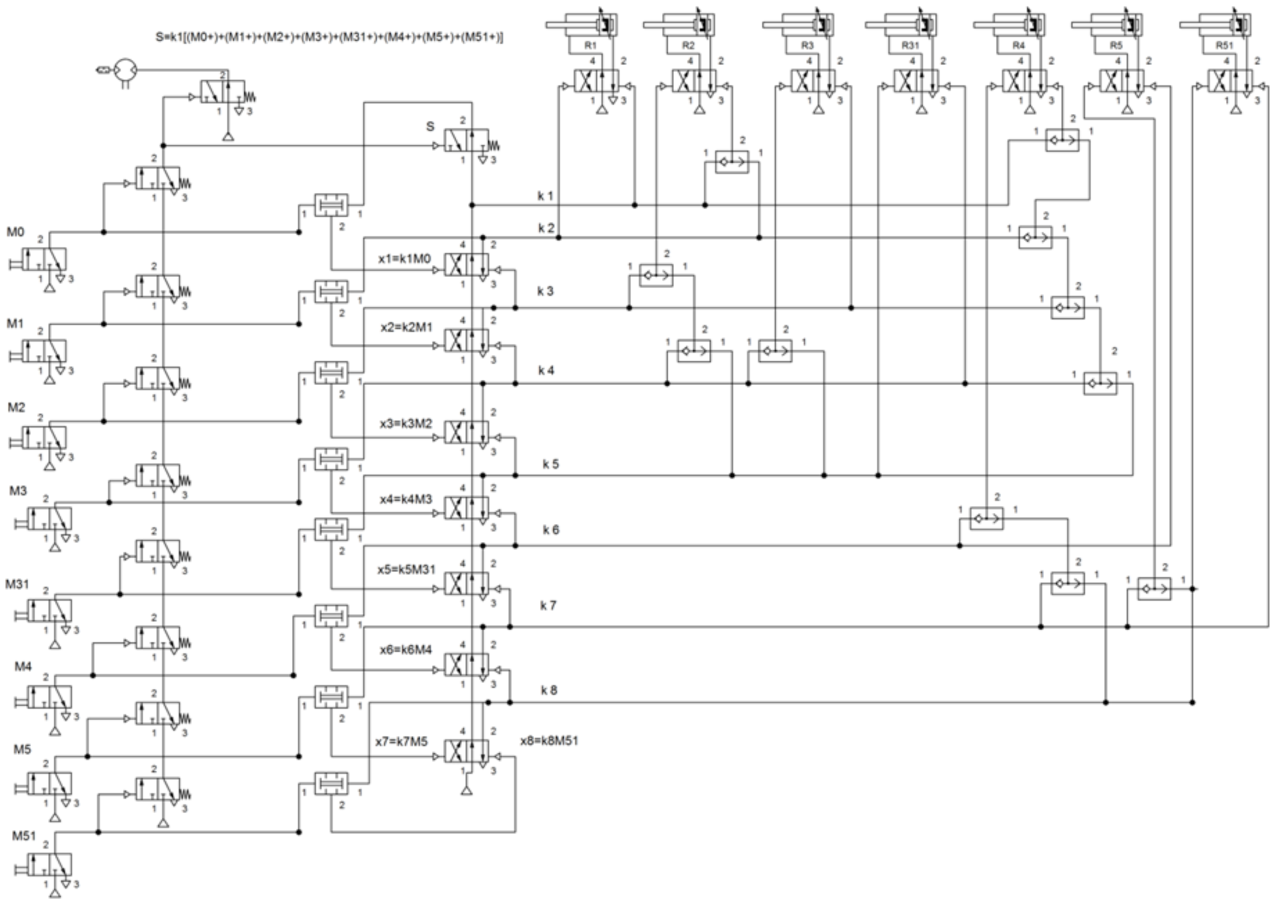

Fig. 10. Sequential control system for filling spiral storages for rolling elements

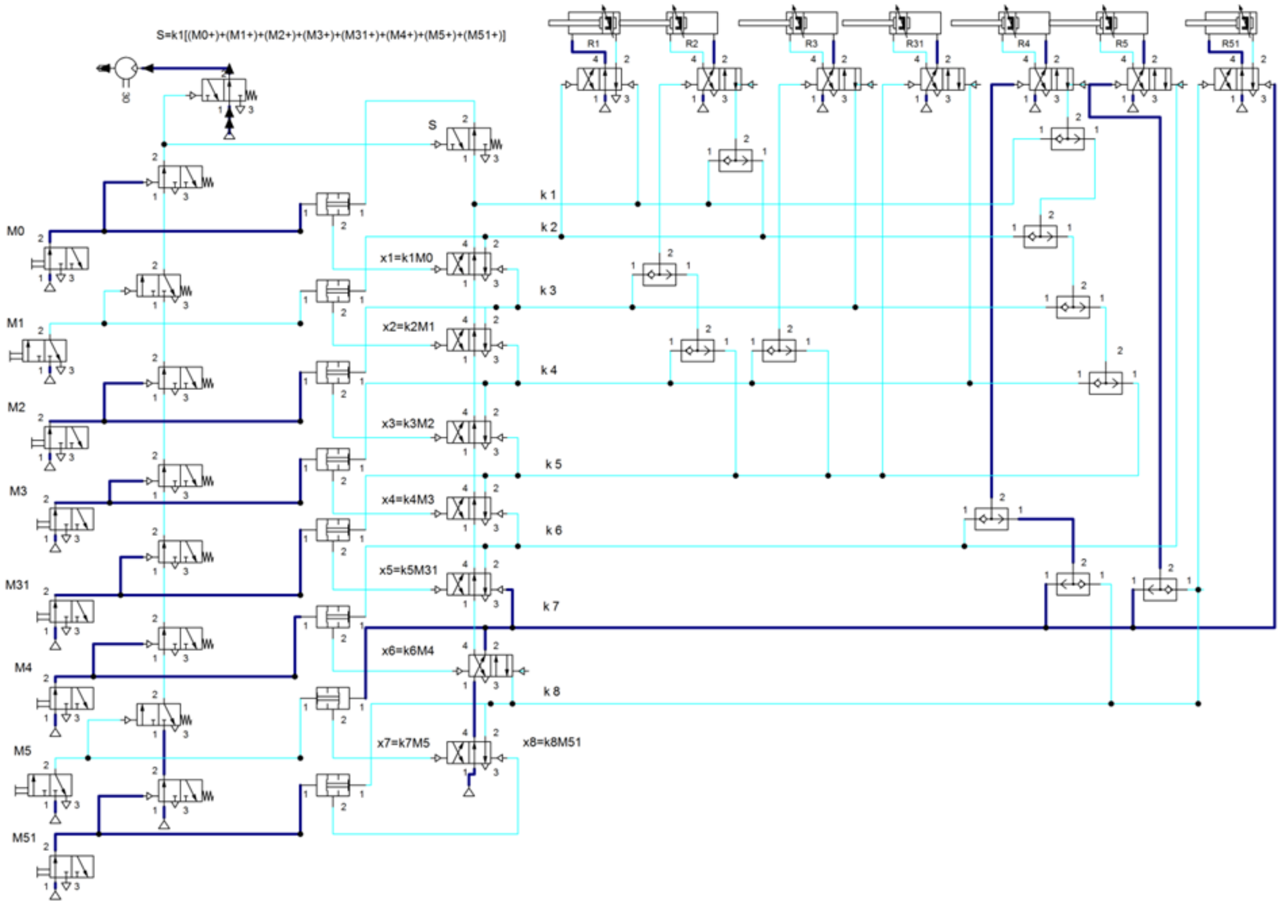

Fig. 11. Simulation of the sequential control system for filling spiral storages for rolling elements

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– once storage M0 is filled (logic state 1), storage M2 is filled, with distributor R2 switched on (setting to state 1) and distributors R3 and R4 switched off (logical state 0);
– once storage M2 is filled (logic state 1), storage M5 is filled, with distributors R4 and R5 switched on (setting to state 1) and distributor R51 switched off (logic state 0);
– when storage M5 is filled (logic state 1), storage M51 is filled, with distributors R4, R5 and R51 switched on (setting to state 1);
– when the M51 storage is filled, the rolling element feeder is switched off;
– the M31 storage is then declared for filling, distributors R2, R3 and R31 are in the on state (logic state 1), manifold R4 is off (logic state 0) and the rolling element feeder is switched on;
– once storage M31 is filled (logic state 1), storage M5 is filled, with distributors R4 and R5 switched on (setting to state 1) and distributor R51 switched off (logic state 0); and
– once storage M5 (logic state 1) is filled, the empty storage is filled again in sequential order from M0 to M51, etc. – the cycle repeats.

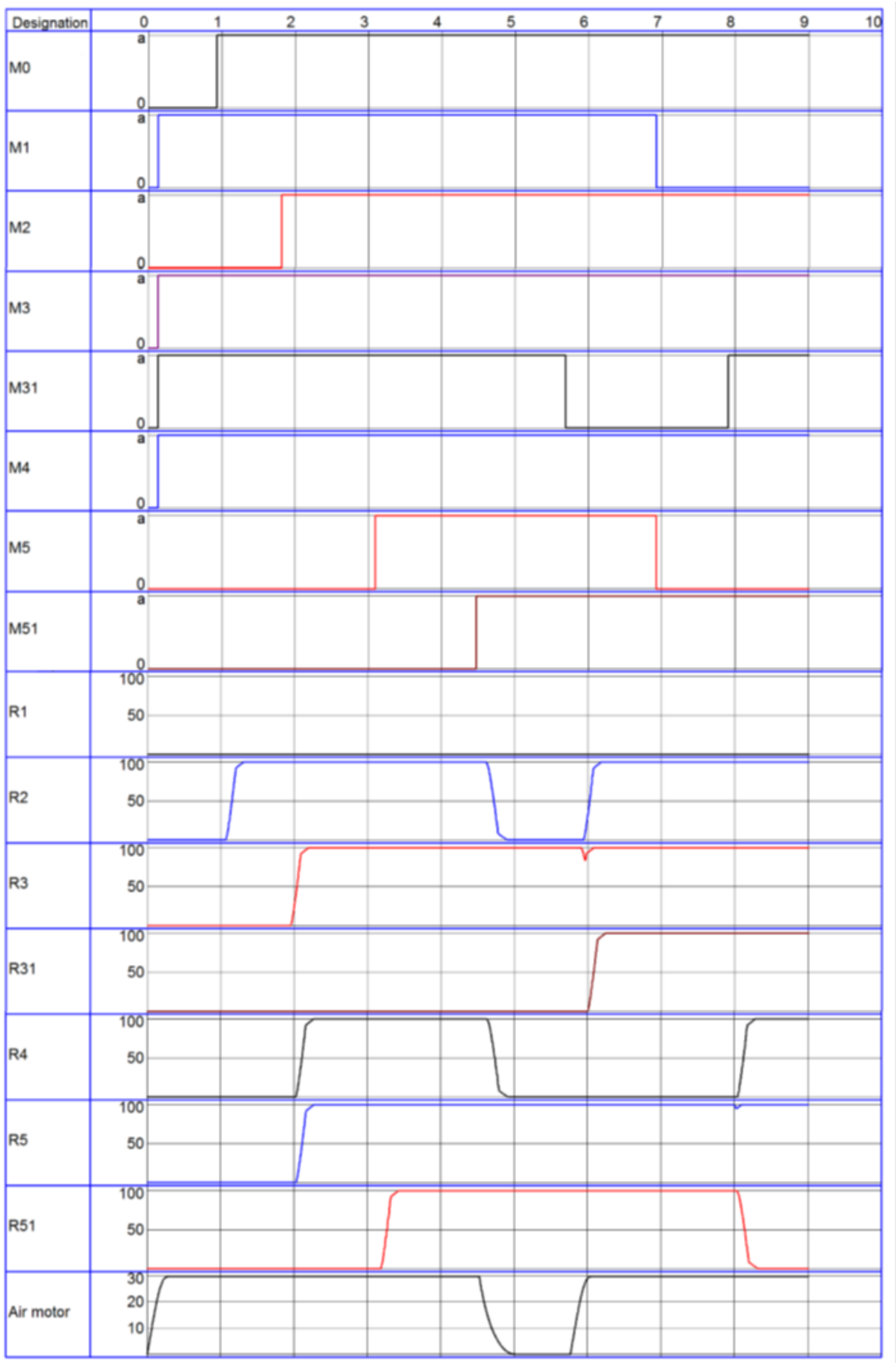

Fig. 12. Cyclogram of the sequential control system for filling spiral storages for rolling elements

It should be emphasised that in order to initially characterise the mass service system, three basic parameters must be identified: the intensity of the notification stream, the intensity of the service process and the rule of the queue [26]. The average intensity of the notification stream (λ) is defined as:

$$\lambda = 1/t_\lambda$$

where t_λ represents average time interval between successive notifications flowing into the system in the examined period.

The average service stream intensity (μ) is defined as:

$$\mu = 1/t_\mu$$

where t_μ represents the average time of handling a single notification in the analysed period.

If the stream of requests has a Poisson distribution, the intensity of service is described by an exponential distribution and first in first out (FIFO) discipline is maintained in the queue, then the functioning of such a system [27] can be expressed by the system utilisation rate (ρ), also called the Erlang constant:

$$\rho = \lambda/s\mu$$

where s represents the number of service desks designed to be serviced.

If ρ >1 at $t \rightarrow \infty$, the queue grows to infinity (system is unstable), while when ρ <1 the queue problem does not exist (system is stable). When $\rho = 1$ (indicating that the system is on the verge of stability) and $\rho > 1$ (indicating that the system is unstable), then the system's operation would not be not very practical under the above assumptions. The system stability condition is: $0 \leq \rho < 1$. The target reduction of the queue to the zero level ($Tk \rightarrow 0$) at a certain intensity of the call stream ($\lambda = const$) can be achieved in two ways, either by reducing the time ($\mu \rightarrow min$), or by increasing the number of service desks ($S \rightarrow max$). In the case of single-station service, the appropriate service capacity should be selected (in the system considered, the capacity of the vertical lift of the rolling elements), which in turn can reduce the time of magazine service.

6. CONCLUSIONS

Testing of the designed pneumatic control system allows us to conclude that:

- by synthesising the system, according to the procedure outlined, it is possible to quickly obtain a control system for any configuration of the transport route for the delivery of components to storages in inter-operational transport;
- by using a two-level control of the filling level of the storages, it is possible to control the emptying status of the storages as a function of the technological time of removal of the items from the storage between the two control points;
- by using a system for the execution of the rise and fall delay of the input signal, short-term states of the presence and absence of an element in the sensor's area of operation are eliminated, which makes it possible to determine an unambiguous state of the presence (absence) of an element in the sensor's area of operation; and
- the time delays of the sensor cooperation system are set according to the speed of movement of the elements in the sensor control zone.
- The designed solution of pneumatic systems is dedicated to the control of process lines in intermediate transport in the production of rolling bearing components, especially inner and outer bearing rings.
- The designed pneumatic system for the execution of the head and rear delays of the input signal with adaptive technological time has been applied for a patent to the Patent Office of the Republic of Poland.

Further research will aim to develop methods and principles for creating control systems for transport routes for the delivery of components to storages in inter-operational transport using electronic systems and PLC programming ladder diagrams.

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