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Analyzing Delay Characteristics in a Pneumatic Pressure Controller

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Abstract

The efficiency and safety of pneumatic brake systems in rail vehicles are vital for the transportation industry. Taking this into consideration, this work investigates the properties and classification of inherent delays within these systems, which are crucial for the proper implementation of advanced safety algorithms. The research focuses on the data collection and analysis of a pressure controller included in the brake system of a rail vehicle, emphasizing the delays originating from several sources, such as solenoid and membrane valves. Experimental data, including response times and pressure ratios, was gathered both from the laboratory provided by Knorr-Bremse Rail Systems and from simulations on a validated Simulink model. Analysis reveals two primary delay sources, being it the fact that solenoid valves exhibit magnetic delays, ranging from 8 to 12 ms. Furthermore, membrane valves exhibit longer delays, approximately 20 ms, attributed to opening and closing times until the required pressure ratio is achieved. Pressure dependence studies indicate minimal influence on delay within the 1 to 7 bar range, showing linear approximations where differences were observed.

Keywords: Pneumatic systems, delay analysis, solenoid valves, membrane valves, pressure dependence, rail vehicles, safety algorithms, EP2002 3.0 brake control device.

1. Introduction

Considering that pneumatic systems are widely used in several subsystems of rail vehicles, especially in brake applications, industry experts have been focusing on the understanding and manipulation of delay times, allowing the implementation of sophisticated anti-lock braking algorithms, even in such heavy vehicles [1].

In the pursuit of safety, reliability, and efficiency, leading companies invest significantly in these areas, recognizing that even the slightest improvement contributes to sustainability, passenger safety, and, not least, the reception of substantial contracts, which are requirements for business continuity.

Having this in mind, the global company Knorr-Bremse Rail Systems will be introducing its new brake control device, the EP2002 3.0, in 2024. This state-of-the-art equipment provides optimum safety, and, due to its complex control algorithm, it incorporates interesting features such as automatic wheel slide protection and derailment detection assistance [2]. Therefore, to enable trains to interpret these situations accurately and respond before the conductor, engineers must consider all possible aspects, including the delays inherent in pneumatic systems [3].

Many studies are based on these properties, requiring a comprehensive understanding of delay characteristics in pneumatic systems. For example, active control techniques, such as time delay control, are applied to pneumatic isolators to improve their isolation performance in the low-frequency range where passive techniques are not appropriate. This delay-based control technique is simple, robust, and easily applicable to real-world systems, whether exhibiting linear or nonlinear behavior [4].

Exploring these inherent delays and defining standard behaviors is crucial for engineers designing pneumatic systems. Delays either need to be minimized or considered in the control logic. Therefore, this study focuses on analyzing the delays observed in the model of a pneumatic system. The goal is to investigate the time elapsed from the electrical command to fill a train's brake cylinder until the pressure starts to rise inside the cylinder, and to explore the time taken to exhaust this cylinder and release the train's brakes. Moreover, the research also seeks to determine if there is a pressure-dependent relationship influencing the magnitude of delay generated by the analyzed system, and classify the data according to source, and magnitude.

It's important to note that this study revolves around the digital pressure controller for a single boogie of a general rail vehicle. The measurements are gathered from the pneumatic laboratory provided by Knorr-Bremse Rail Systems, and simulations are conducted based on the model developed in the works "Modelling the Dynamics of Membrane Valves Applied to Pneumatic Brake Systems in the Rail Industry" [5] and [6].

2. Theoretical Background

Pneumatic systems may inherit delays from several sources, which can affect their performance, especially if the system has a time-domain-based control. Considering the totality of the system, such set of events can be generalized as the response time: every pneumatic system has a specific response time, indicating the duration required for the system to react to a change in input. This delay originates mainly from the system components, inherent inertia and the time taken for air pressure to build up or dissipate, but other sources might be present.

In the sub-system level, one possible source could be the compressed air supply. Even though not common in rail vehicles, there is the possibility of a time interval between activating the compressor and the system receiving an adequate air supply. It is also valid to mention the dependability of the piping characteristics, which varies based on factors such as tubing length, diameter, and airflow rate influence.

At the component level, it is possible to mention the valve response time, which will be explored in detail during this research. Valves have their own response time, being the duration, it takes for them to fully open or close in response to a control signal. Naturally, a similar phenomenon is observed in the brake cylinder since such systems may present a delay between activating the valve and the cylinder's actual movement. This delay arises as air pressure takes time to build up inside the cylinder and overcome factors like friction and the load being moved.

Indirect sources of delay are also present in pneumatic systems, such as increased response time due to pressure drops within the system, which can be due to restrictions in piping, sealing, and even leakages in the system. Identifying and repairing leaks are crucial for maintaining the safe operation of the system [7].

In air logic control systems, time delays play a critical role and can be specifically classified between fixed or adjustable system-inherent time delays, or artificially generated delays, which are originated by modifying the geometry, applying software assistance, or adding new components [8]. Focusing on magnetic systems, delays can come from several factors as well. For example, magnetic saturation, a phenomenon where magnetic materials reach their limit in supporting magnetic flux, leads to delays as the material transitions between saturated and unsaturated states. Also, hysteresis, the lag between magnetic field and flux density changes, and eddy currents induced in conductive materials by changing magnetic fields are additional sources of delays. In some cases, delays can also occur due to the elasticity of materials or the inertia of moving parts in magnetic components [9].

The control system response time is another factor affecting magnetic systems. Delays can be introduced when manipulating magnetic fields, especially in real-time applications. Energy losses in the form of heat due to resistance in conductive materials can impact system efficiency, also environmental factors like temperature and humidity variations can affect magnetic materials, both leading to inherent delay [10].

On a rail pneumatic system, focus can be directed to membrane and solenoid valves, commonly used components which have response times influencing system operation, especially in applications requiring rapid or precise control. Air flow rate and the size of valves and orifices are key points; smaller valves respond faster due to reduced air volume. Pressure build-up time, especially in systems relying on compressors or tanks, introduces delays until sufficient pressure is generated for proper operation as well. A brake cylinder volume, for example, may also impact delays, since larger cylinders would demand more time to be filled. The characteristic equation of filling a brake cylinder of a rail vehicle is available below:

$$\dot{P}_{cyl} = P_{supply} \cdot C_c \cdot \alpha \cdot \psi\left(\frac{P_{cyl}}{P_{supply}}\right) \quad (1)$$

Being C_c the choke diameter in the charging valve, and ψ is the flow function in function of the pressure ratio between the brake cylinder and the supply pressure. α is a constant containing geometrical and physical properties of the system. For exhausting the cylinder, which also has a

time delay, the following equation is the guideline for modelling, being C_v the venting choke diameter geometrical property:

$$\dot{P_{cyl}} = P_{cyl} \cdot C_v \cdot \alpha \cdot \psi\left(\frac{P_{atm}}{P_{cyl}}\right) \quad (2)$$

As visible, a direct term for the delay is not present, since it can be originated from several sources at the same time, and it is not trivial to individually identify then, for example, air leakages, which leads to pressure decreases, which slows cylinder movement, or pneumatic hysteresis, a phenomenon where components respond differently for the same input signal based on pressurization status, can both be key factors for delay times as well [11].

When it comes to pneumatic valves, their response time depends on several key factors. Valve type, including solenoid valves, membrane valves, spool valves, and poppet valves, influences response times. Smaller valves with reduced orifice volumes respond faster than larger ones. The internal design, especially the shape and configuration of valve components, impacts response time. Valves designed for rapid actuation feature optimized components for quick opening and closing [12].

The supply pressure is also a factor to be considered; higher pressures result in faster response times, crucial in applications requiring rapid movements. Air flow rate through the valve orifice is critical; larger orifices or higher flow rates enable faster air exchange, leading to quicker response. Additionally, the quality and condition of valve components, including seals and moving parts, influence response time.

Therefore, on an electro-pneumatic system, magnetic delays and pneumatic delays from multiple sources will act on the system simultaneously. For rail applications related to pressure control on mechanical brakes, they may be classified in just three:

- Electromagnetic delay
- Membrane delay
- Total delay

3. Methodology and Equipment

Due to the high complexity of individualizing this multi-origin phenomenon and the high non-linearity of pneumatic systems, the investigation will be conducted mainly on experimental and simulated data, divided into three main groups:

- Initially, regarding the electromagnetic delay, an investigation of the valve response times based on the supply pressure value will be conducted. The data from this section was collected on a test bench.

- Afterwards, regarding the membrane delay, an investigation of the time consumed by the membrane before starting to fill or exhaust a brake cylinder, and similarly, considering different supply pressure values, will be simulated. The data from this section was collected on a Simulink model previously developed, verified, and validated.

- Finally, the total delay will be verified, which regards the response time of the system between the command and the detection of the response.

A sketch of the system can be seen on the figure below, being it valid not only for the test rig, but also for the Simulink model:
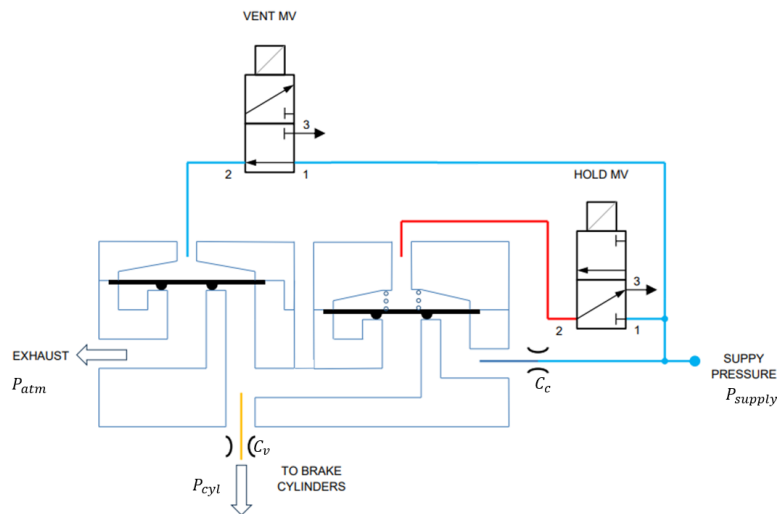

Figure 1: Sketch of electropneumatic system to be investigated in respect to delay characteristics.

3.1 Electromagnetic Delay

This specific characteristic is determined through the following method: an electric command is sent to the controller, requesting a valve to change its position. Pressure curves, depicting the relationship between pressure and time, were collected in a dedicated test rig at the Knorr-Bremse laboratory, utilizing advanced pressure sensors. After the curves have been exported and the electrical signals are plotted in the same file, the time interval between the command and the subsequent alteration in pressure within the valve's output channel is measured assisted by a curve visualization software, named FAMOS reader.

These measurements are conducted for both the hold magnetic valve and the vent magnetic valve, with several initial condition's value. One example can be seen below, in which the blue curve is the electrical logic command for the valve and the red represents the pressure in the output of the valve [bar] in function of time, in which the initial condition was a value of 6.35 bar.
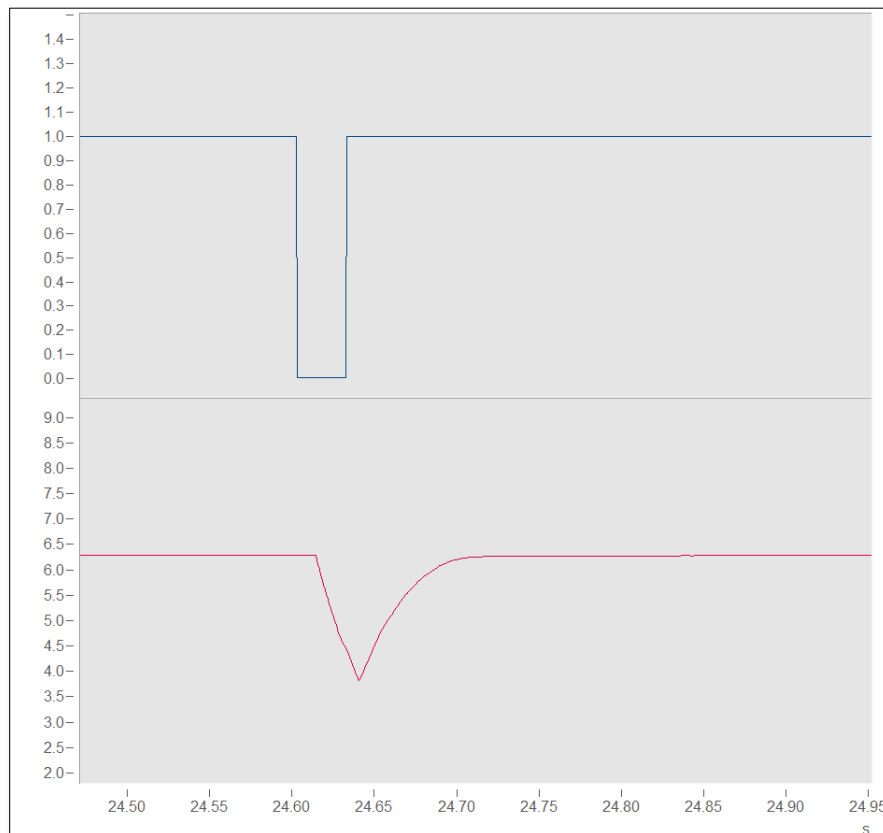

Figure 2: Example of measurement analysis regarding delay characteristics on FAMOS software.

Followed by the activation of measurement cursor's tool on the software, the data can be collected as visible on the figure 3:
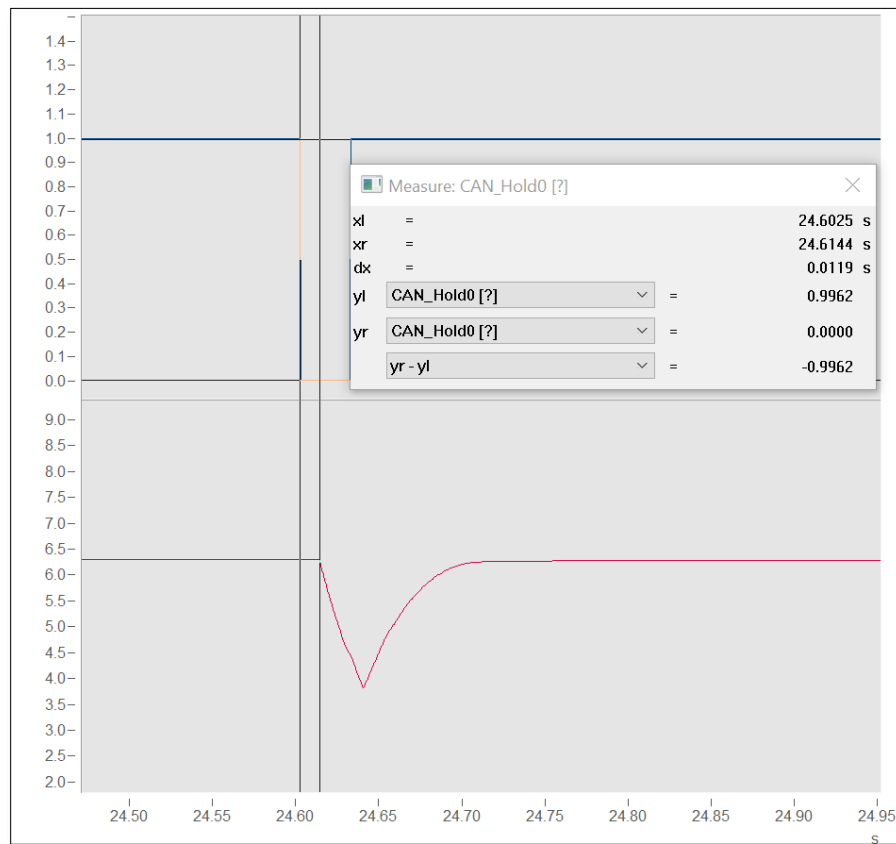

Figure 3: Example of measurement analysis using cursors regarding delay characteristics on FAMOS software.

3.2 Membrane Delay

The control mechanism for membrane valves differs significantly from that of magnetic valves. As demonstrated in this study, the state of membrane valves relies on a pressure ratio rather than a straightforward signal. Consequently, a Simulink model has been developed to replicate the pressure controller applied in section 3.1.

In this simulation setup, a signal representing the membrane's state is incorporated into the model. As illustrated in the diagram, the operation of the hold membrane is dependent on the ratio between the supply pressure and the input pressure of the hold control channel. Similarly, the vent

membrane operates based on the ratio between the brake cylinder pressure and its corresponding vent control channel pressure.

By conducting simulations with different supply pressures, it is possible to analyze the behavior of membrane valves, aiming to verify the duration between the initiation of pressure rise/decay in the input channels and the actual opening of the membrane. This can be done as seen on the figure 4, by inserting a scope with 3 inputs for visualizing the signals.
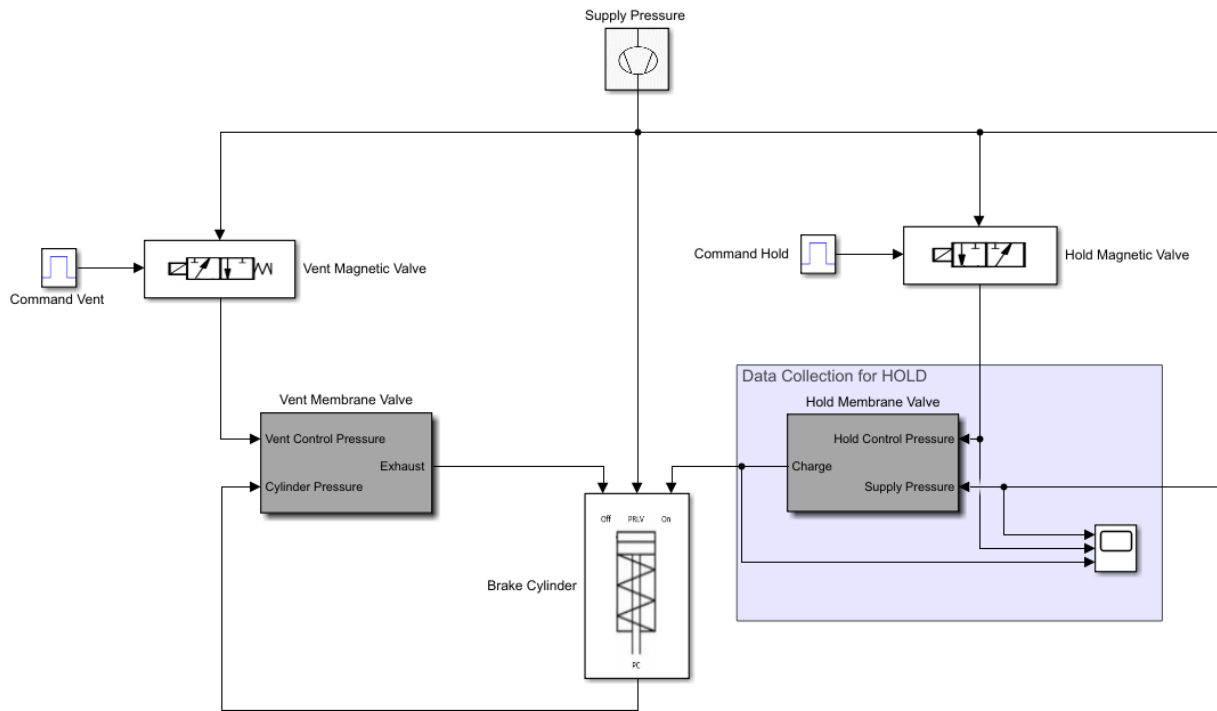

Figure 4: Example of measurement analysis using Simulink Model.

One example of the data that becomes available on the scope after running a simulation can be seen on the figure 5:
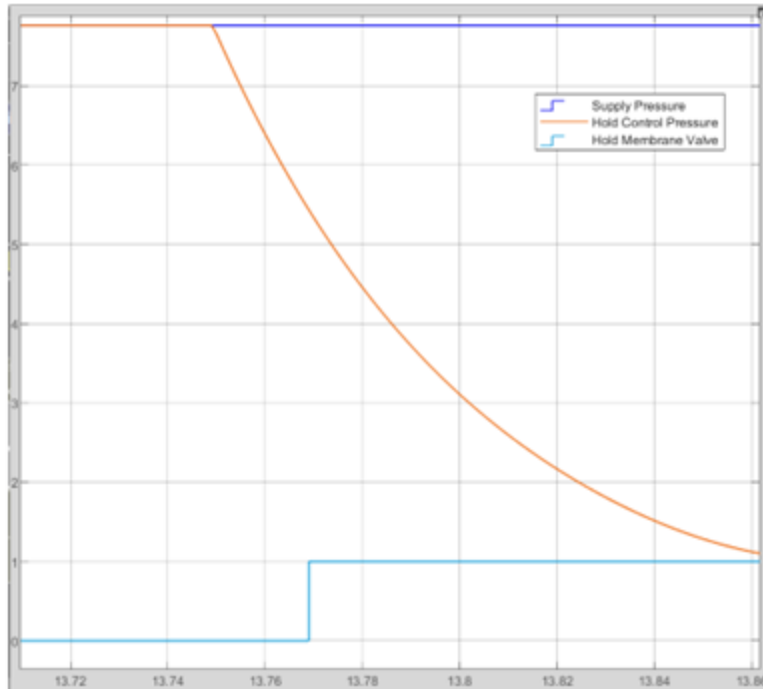
Figure 5: Example of data visualization using Simulink Model for the membrane delays.

And by applying the Simulink cursor's tool for collecting the time information, it is possible to measured for how long after the pressure started to be exhausted on the control channel, the state of the membrane switched:
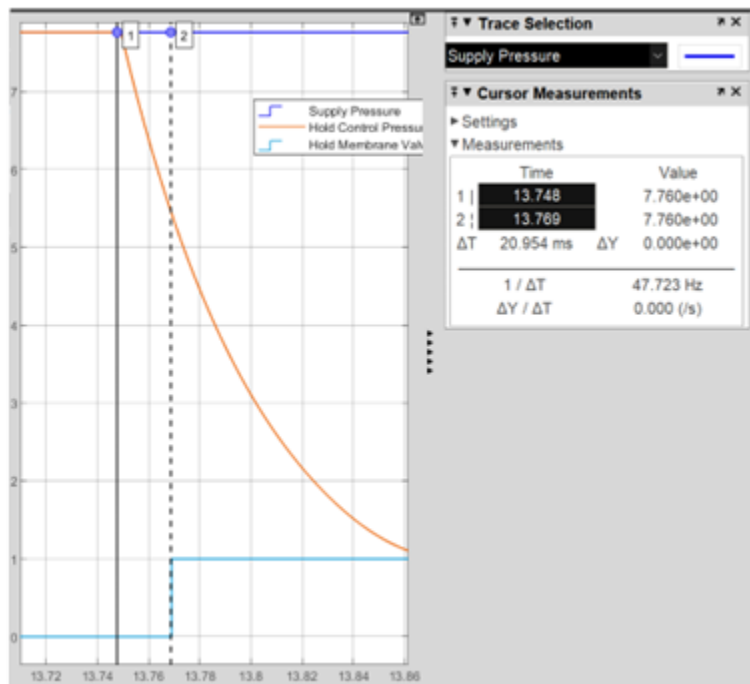

Figure 6: Example of data acquisition with cursor using Simulink Model for the membrane delays.

3.3 Total Delay

On a real-life scenario, total delay includes not only the magnetic and membrane delays, but also from the multiple unidentified sources within the system. In the model, the total delay combines magnetic and membrane delays and inherent delays from the system have been neglected.

To quantify this delay, the measurement is performed between the moment the electrical command is issued by the controller for the magnetic valve until the pressure begins to increase inside the brake cylinder, for a charging command, and of course if venting, until the pressure begins to decrease. Given that the model has been validated, data can be directly collected using the following setup for the charging process:
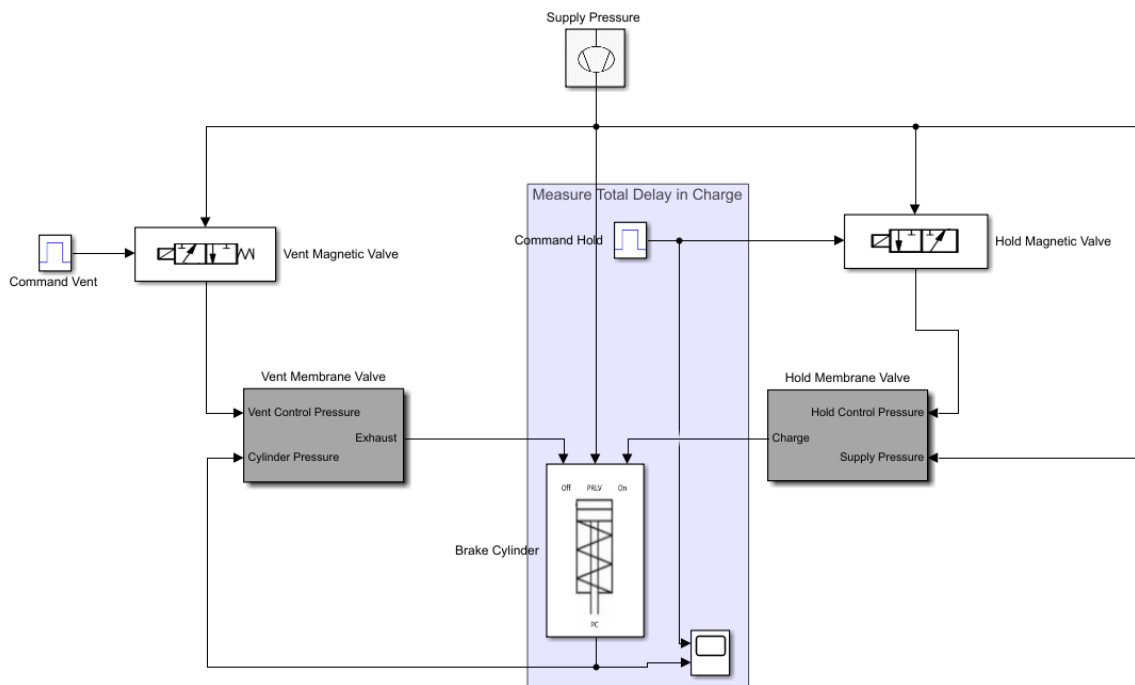

Figure 7: Example of measurement analysis using Simulink Model for total delay during charge of the cylinder.

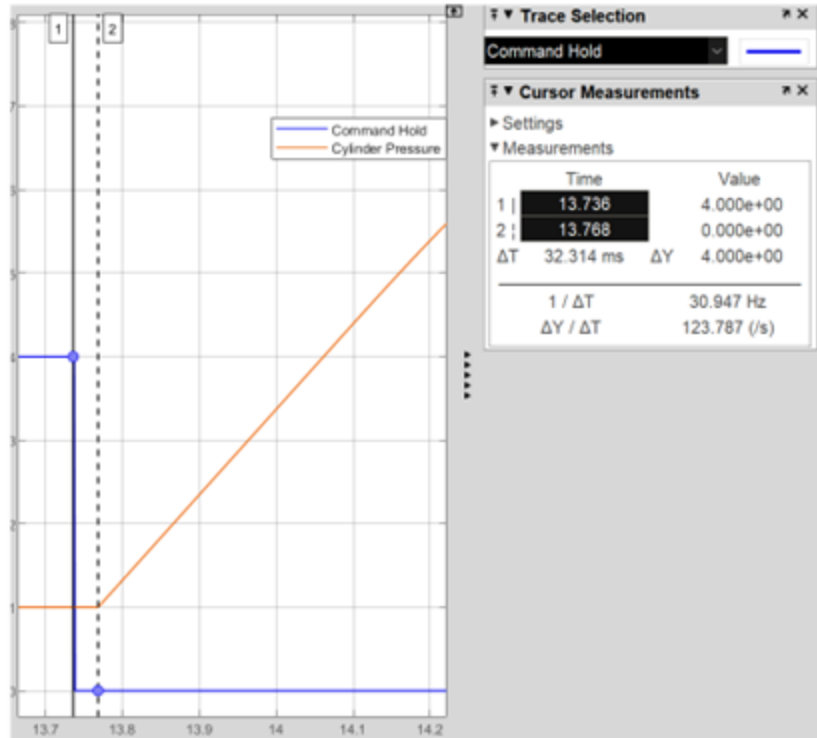And an example of the data available on the scope would be:

Figure 8: Example of data acquisition with cursor using Simulink Model for the total delay.

In summary, using supply pressure values of 2,4,6 and 7 bar, the following measurements should be conducted:

- Electromagnetic delay in the hold magnetic valve.
- Electromagnetic delay in the vent magnetic valve.
- Membrane delay on the hold magnetic valve.
- Membrane delay on the vent magnetic valve.
- Total delay in charging the brake cylinder.
- Total delay in venting the brake cylinder.

Therefore, a plot will be generated for 6 bar supply pressure from each specific situation, illustrating the data visually. Additionally, a comprehensive summary of all the collected information will be presented in tables for a clear overview. Furthermore, a graphical representation will be plotted to illustrate the dependency of delay on the supply pressure, clarifying if pressure dependance is relevant or not.

4. Results

4.1 Electromagnetic delay in the hold magnetic valve

The example measurement realized for 7 bar of supply pressure, can be seen on the plot below, being the blue curve the pressure in the output of the valve, and the red valve the electric signal on the magnetic valve. It is important to be aware that the pressure in the channel does not reach the supply pressure due to the construction of the system.
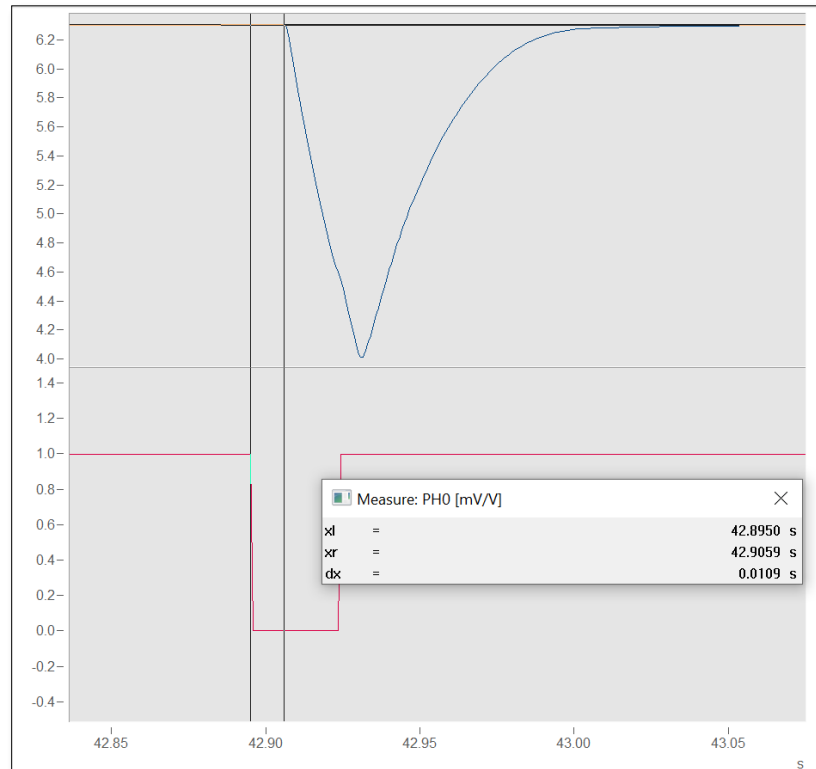

Figure 9: Delay between activation and valve response for hold magnetic valve for supply pressure set a 7 bar.

Therefore, it is possible to see that the time elapsed between the command was given to the valve, and the response was of 10.9 milliseconds, for this case. The results collected for the other supply inputs are available in the table below:

Supply Pressure [bar]	Time elapsed [ms]
2	10.3
4	10.9
6	10.5
7	10.8

Table 1: Delay between activation and valve response for hold magnetic valve in function of the supply pressure.

4.2 Electromagnetic delay in the vent magnetic valve

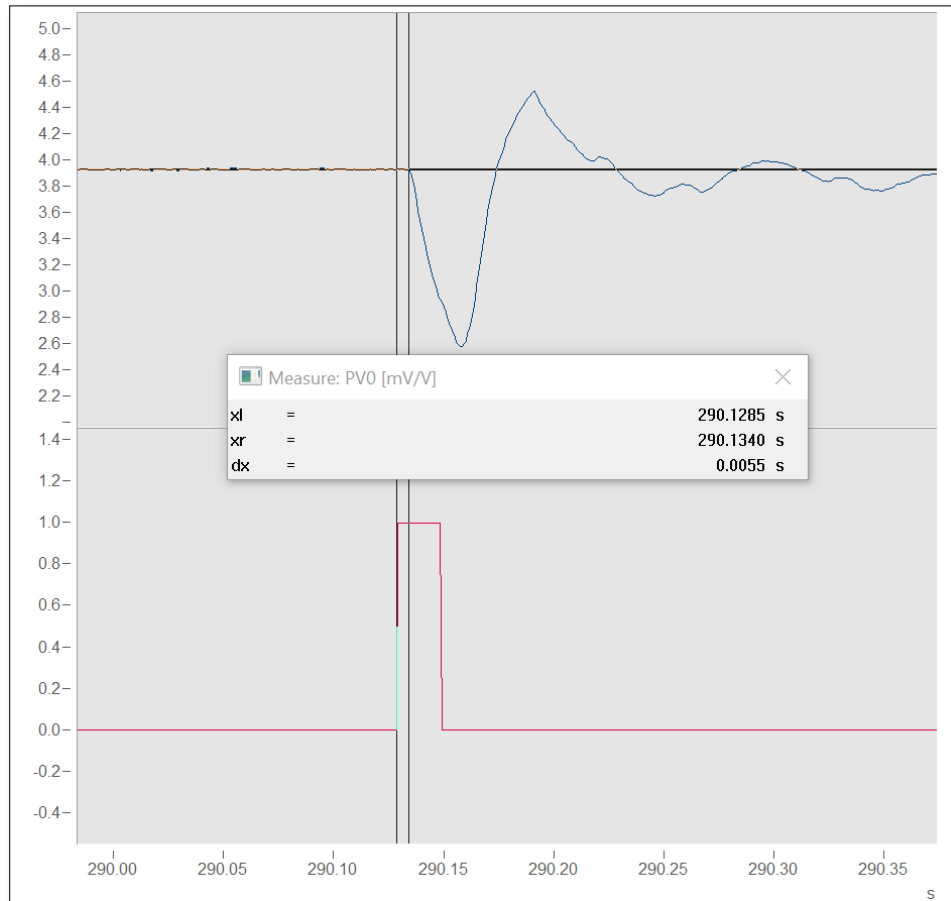The measurement realized for 7 bar input as the supply pressure is available below:

Figure 10: Delay between activation and valve response for vent magnetic valve for supply pressure set a 7 bar.

And the remaining tests:

Supply Pressure [bar]	Time elapsed [ms]
2	4.9
4	5.5
6	5.9
7	6

Table 2: Delay between activation and valve response for vent magnetic valve in function of the supply pressure.

4.3 Membrane delay on the hold membrane valve

As previously mentioned, the results from this section onward are collected in the Simulink model, therefore the time elapsed between the pressure was modified until the switch in the membrane state can be seen below.
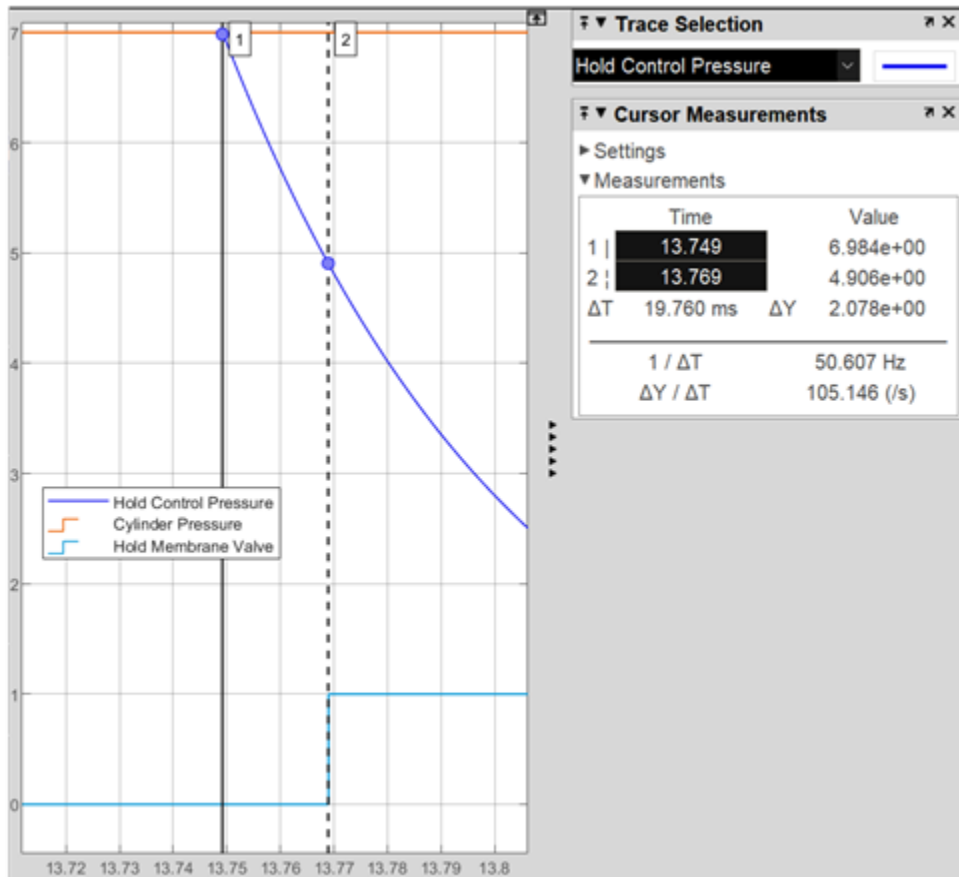

Figure 11: Delay between change in control pressure and membrane state switch for the hold membrane valve with supply set at 7 bar.

For this supply pressure of 7 bar, the delay was of 19.76 ms. The results for the different tests can be seen on the table below:

Supply Pressure [bar]	Time elapsed [ms]
2	19.69
4	19.86
6	19.94
7	19.76

Table 3: Delay between change in control pressure and membrane state switch for the hold membrane valve.

4.4 Membrane delay on the vent membrane valve

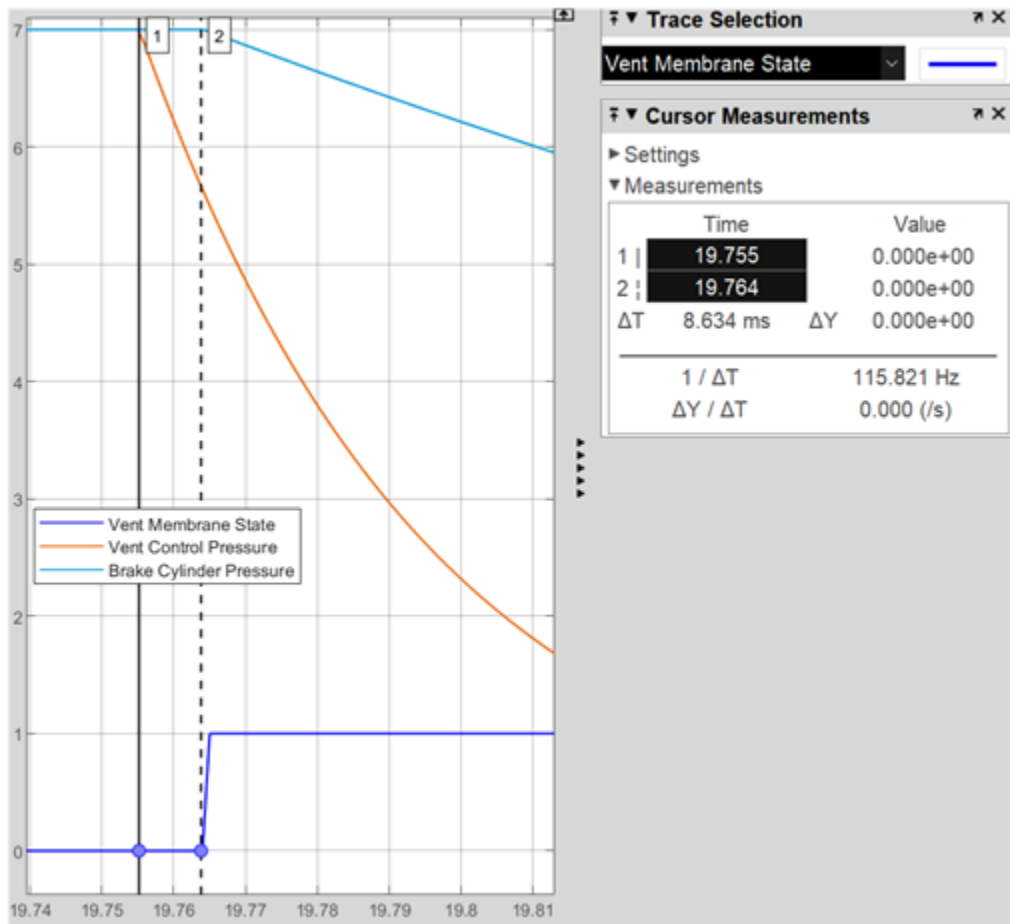And for the vent membrane valve:

Figure 12: Delay between change in control pressure and membrane state switch for the vent membrane valve with supply set at 7 bar.

Therefore, for the supply pressure of 7 bar the delay was of 8.64 ms. The other simulated values can be seen on the table below:

Supply Pressure [bar]	Time elapsed [ms]
2	0.9
4	10.92
6	10.92
7	8.64

Table 4: Delay between change in control pressure and membrane state switch for the vent membrane valve.

4.5 Total delay in charging the brake cylinder

The time elapsed between the hold electric command is given until the brake cylinder starts being filled, for 7 bar of supply pressure can be seen on the figure 13, bringing a value of 32.99 ms.
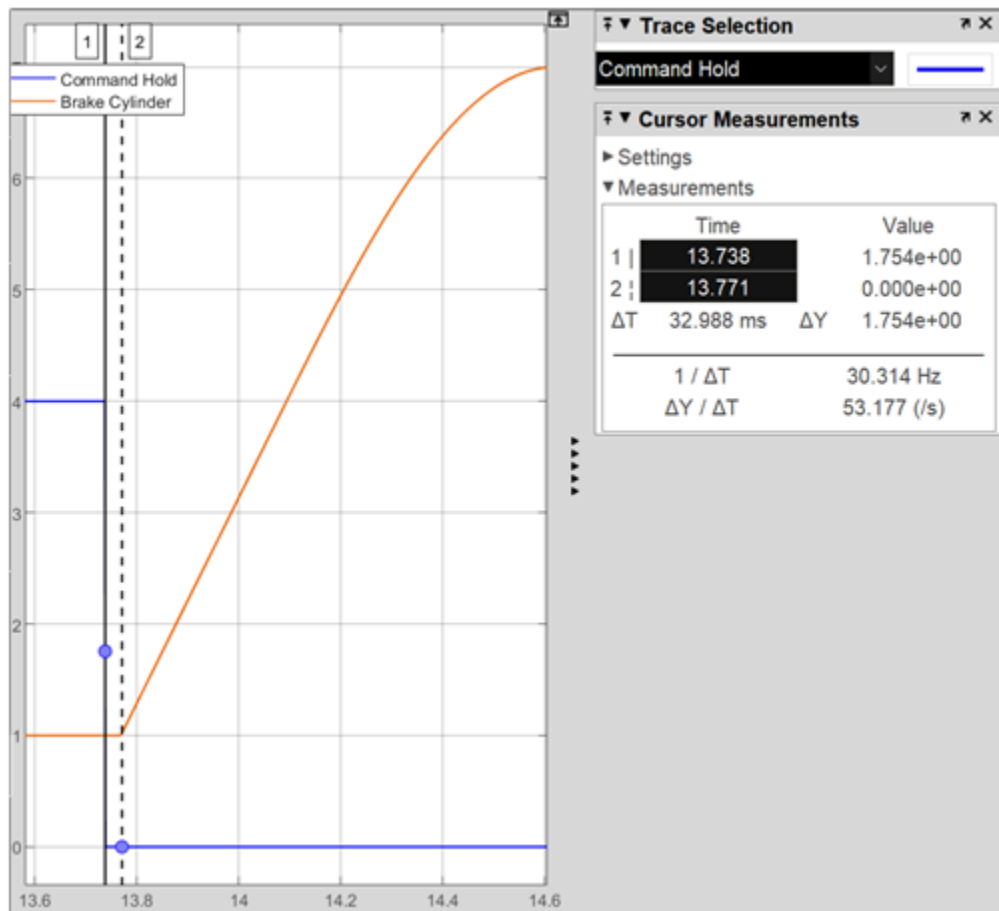

Figure 13: Total system delay between the request to charge the brake cylinder and the pressure raise on it, for 7 bar of input pressure.

The remaining simulation results are available on the table 5:

Supply Pressure [bar]	Time elapsed [ms]
2	30.78
4	30.12
6	30.33
7	32.99

Table 5: Total delay for the charging of the brake cylinder.

4.6 Total delay in venting the brake cylinder

For the venting of the brake cylinder, the value for 7 bar input was of 13.28 ms, as visible on the figure 14.
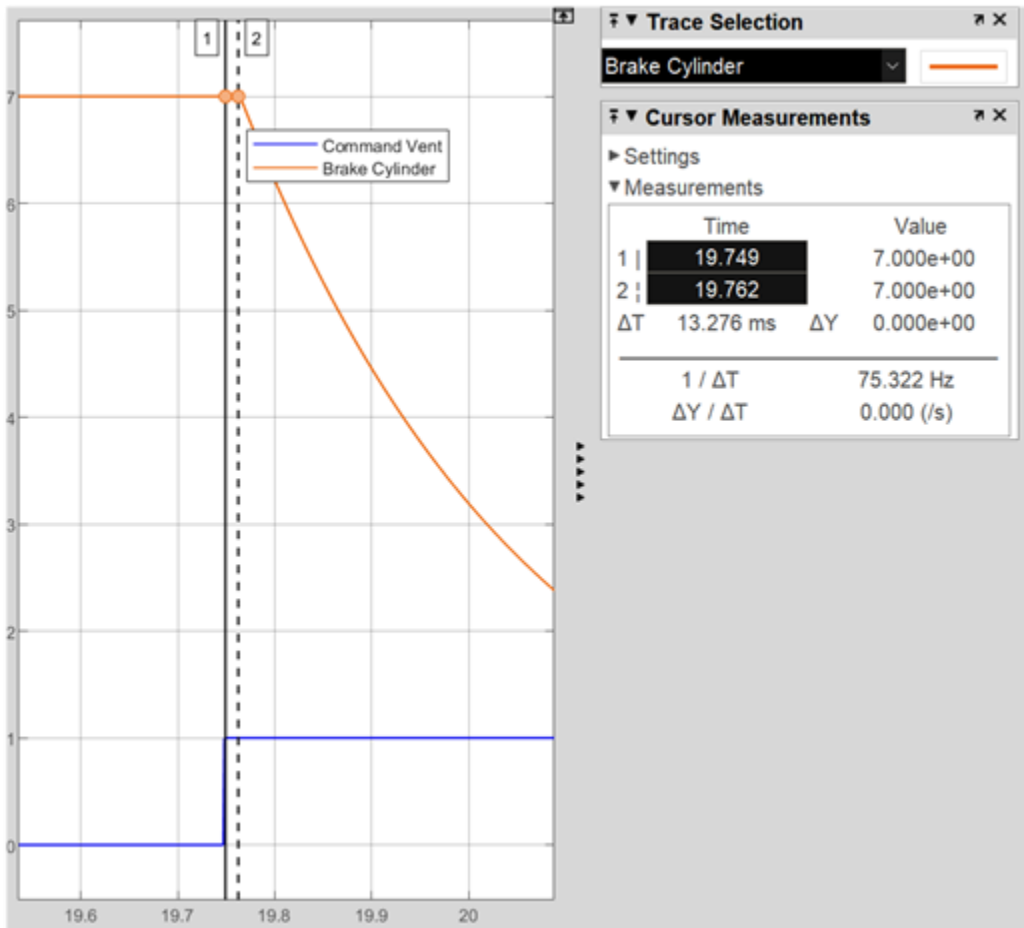

Figure 14: Total system delay between the request to exhaust the brake cylinder and the pressure decay on it, for 7 bar of input pressure.

And for the remaining values:

Supply Pressure [bar]	Time elapsed [ms]
2	9.11
4	20.25
6	18.86
7	13.28

Table 5: Total delay for the exhausting of the brake cylinder.

5. Conclusion

Therefore, by analyzing the results it can be concluded that the electromagnetic delay in the hold solenoid valve appears to be independent of pressure, making it suitable for constant approximation in control applications. On the other hand, the vent solenoid shows a faster response, likely due to the differences in choke diameters. Despite this, there's no substantial evidence of pressure dependence.

Examining the membrane delays becomes evident that the hold membrane experiences longer delay compared to magnetic delays, averaging at 19.81 ms. Figure 11 shows clearly that the additional time required is due to the control volume exhausting until the membrane threshold is reached. In contrast, the vent membrane demonstrates a faster response, like magnetic delays. Surprisingly, while constant values are observed for intermediary supply conditions, non-linear pressure dependence is detected at the boundaries of 7 and 2 bar. The valve's dependence on brake cylinder pressure, coupled with control pressure characteristic curve (as shown in Figure 12), could explain this behavior. Further research is recommended to explore this case.

Considering the total delay, which combines both magnetic and membrane delays, it's evident that charging the cylinder using hold components results in a relatively constant value with minimal pressure dependence. However, during the exhaust phase using vent components, a non-linear pressure dependence is noticeable. This finding suggests the need for a closer investigation into the causes, possibly incorporating a model that accounts for thermal effects on the system.

The results obtained from this study have significant implications for the development of brake control algorithms. The unexpected non-linear pressure dependence in the exhaust delay demands further exploration. Additionally, while inherent delays from unknown sources exist in the system, they prove negligible for practical brake control applications.

References

[1] Miller, J. I., & Cebon, D. (2012). **An investigation of the effects of pneumatic actuator design on slip control for heavy vehicles**. Vehicle System Dynamics, 51(1), 13-16. DOI: 10.1080/00423114.2012.717703

[2] Knorr-Bremse Media. **Customer Magazine Informer**. Available at https://rail.knorr-bremse.com/media/test_e/6400_publications/6420_customer_magazine_informer/informer_50/informer_50_e.pdf. Accessed on October 20th, 2023.

[3] Knorr-Bremse. **Grundlagen der Bremstechnik**. Knorr-Bremse private library, 2017.

[4] Shin, Y.-H., & Kim, K.-J. (2009). **Performance enhancement of pneumatic vibration isolation tables in low-frequency range by time delay control**. Journal of Sound and Vibration, 321(3-5), 537-553. ISSN: 0022-460X.

[5] Nunes, M., et al. (2022). **Modelling the Dynamics of Membrane Valves Applied to Pneumatic Brake Systems in the Rail Industry**. Individual Project, Budapest University of Technology and Economics, Budapest, Hungary.

[6] Nunes, M. (2022). **Modelling the Dynamics of Membrane Valves Applied to Pneumatic Brake Systems in the Rail Industry**. Eurobrake Conference, Fisita Congress, Barcelona, Spain.

[7] AirTAC USA Corporation. **6 Common Problems in Pneumatic Systems and How to Fix Them**. Available at https://www.linkedin.com/pulse/6-common-problems-pneumatic-systems-how-fix-them-, by AirTAC USA Corporation. Accessed on October 21st, 2023.

[8] Power & Motion Tech. **Basics of Pneumatic Logic**. Available at https://www.powermotiontech.com/home/article/21122363/basics-of-pneumatic-logic. Accessed on November 3rd, 2023.

[9] Halliday, D., Resnick, R., & Walker, J. 2021. **Fundamentals of Physics**. 12th Edition. Wiley Publishing Inc. ISBN: 978-1-119-77351-1

[10] Furtwängler, Ralf. **Modellbildung**. Knorr-Bremse private documentation, 2003

[11] Ogata, K. (2010). **Modern Control Engineering**. Prentice Hall. ISBN: 9780136156734.

[12] Wendt, Lutz. **Taschenbuch der Regelungstechnik**. ISBN 3-8171-1705-1. Verlag Harri Deutsch, 2003.