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DETERMINATION OF OPENING AND CLOSING TIMES OF A PILOT-OPERATED HUNG-TYPE DIAPHRAGM VALVE BASED ON PRESSURE DIFFERENCE: COMBINING EXPERIMENTAL RESULTS AND MATHEMATICAL MODEL

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Abstract

In this study, we investigated the dynamic behavior of a pilot-operated hanging solenoid valve, with particular emphasis on the operating principles of its constituent components. Solenoid valves are crucial for controlling fluid flow in high-speed systems, making it important to understand their response for the proper functioning of the system. The research focuses on the opening response (t_{or}) and closing response (t_{cr}), along with key timing parameters: opening delay (t_{od}), opening time (t_{ot}), closing delay (t_{cd}), and closing time (t_{ct}). An experimental setup was employed to measure pressure changes across a range of differential pressures from 69 to 487 kPa. This research also uses mathematical modeling to simulate time-dependent changes in pressure and flow area, integrating experimental data with model predictions to accurately determine timing values through an optimization algorithm. The fastest opening response was recorded at 29.2 ms under a pressure difference of 82.5 kPa, while the slowest response occurred at 46.1 ms under a pressure difference of 486.1 kPa. In regard to the closing response, the fastest recorded time was 26.8 ms at 281.8 kPa, while the slowest was 37 ms at 22.6 kPa. These results demonstrate a distinct behavior: while the closing response improves with increasing pressure, the opening response declines. Overall, the findings highlight the valve's suitability for applications requiring rapid response and lower pressure differentials, underscoring the critical importance of precise knowledge of operational parameters.

Keywords: dynamic behavior; hung-type diaphragm valve; opening response; closing response; opening delay; closing delay.

1 Introduction

Solenoid valves are electromechanical devices that control the flow of liquids or gases through electrical activation, converting electrical energy into mechanical motion [1]. These devices typically comprise a number of essential components, including a solenoid, plunger, seal, spring, orifice, and ports.

In high-velocity dynamically operating systems, in particular those necessitating rapid action for intake and exhaust processes, it is of great importance to comprehend the behaviour of pilot-operated hung-type solenoid valves in order to ensure optimal functionality. The timing of valve operations has a significant impact on system efficiency, underscoring the importance of their stochastic nature.

The operational principle of solenoid valves exhibits a unique combination of simplicity and sophistication. When an electric current is applied, the solenoid generates a magnetic field that moves a ferromagnetic core, thereby opening the orifice for fluid flow. The stopping of the current enables the spring to return the core to its original position, thus closing the valve.

Solenoid valves can be classified into two primary categories: direct-acting and pilot-operated. Pilot-operated valves employ pressure differentials to enhance energy efficiency, frequently incorporating floating-type or hung-type diaphragms to fulfill particular requirements.

A review of the literature reveals a multitude of studies that have been conducted with a focus on the dynamics and flow characteristics of solenoid valves. Jin et al. [2] identified an inverse relationship between the response time and excitation voltage, as well as a direct relationship with spring pre-compression during start-up. During closing, however, the relationship was inverse.

Dong and Li [3] investigated a parallel-spool pilot-operated solenoid valve design, analysing how its structure enhances flow rates and responsiveness. They employed mathematical modelling and performed experimental validation to determine the impact of factors such as spool geometry on the valve's performance.

Choi et al. [4] conducted an investigation into the use of pilot-controlled solenoid valves in ultra-high-pressure applications. The researchers gathered data on the dynamic response using laser sensors and accelerometers, after which they created a model of the results using MATLAB/Simulink. The experimental approach revealed a two-phase activation process, thereby enhancing the understanding of the valve's operational mechanism.

Jeong et al. [5] used AMESim software to evaluate diaphragm orifice area effects on flow characteristics and dynamics, validating their model with experiments involving pressure drops. They concluded that reduction in diaphragm area increased effective cross-sectional area but did not significantly affect dynamic performance.

This research provides insights into the dynamic behavior of pilot-operated hung-type solenoid valves by examining how flow area, opening and closing responses change under various pressure differences. Understanding the valve dynamics is complicated by configuration variations and the inherent complexity of the design, making it imperative to address these gaps for optimizing applications that require rapid response.

2 Overview of the pilot-operated hung-type diaphragm valve

The pilot-operated hung-type diaphragm valve, whose typical configuration and components are illustrated in Fig. 1, differs from typical pilot-operated solenoid valves in that it does not depend on a minimum pressure differential for operation. The device comprises a valve body and an electromagnetic coil assembly, with a circular elastomer diaphragm placed between the cover and the valve body to serve as a control mechanism for the opening and closing of the main valve orifice. The diaphragm valve provides support for the pilot valve and cup element, thus enabling these components to function as an integrated system.

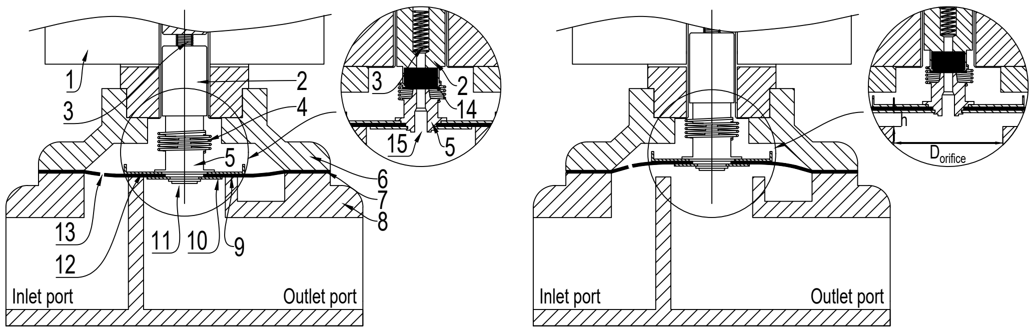

Figure 1: Graphical representation of the pilot-operated hung-type diaphragm valve: normally closed (left) and actuated (right). Electromagnetic coil assembly (1), plunger (2), plunger spring (3), pilot valve spring (4), pilot valve (5), cover (6), diaphragm (7), valve body (8), valve seat (9), lower washer (10), diaphragm valve assembly (11), cup member (12), diaphragm orifice (13), pilot valve disc (14), and pilot-orifice (15).

The energization of the normally closed valve presents two distinct situations. In cases where the net force exerted on the upstream side of the diaphragm is less than the pulling force applied by the pilot spring, the diaphragm is lifted by direct electromagnetic force, exhibiting operational characteristics analogous to those observed in direct-acting solenoid valves. In other cases, line pressure assists in opening the valve, similar to the behavior observed in typical pilot-operated solenoid valves.

3 Data-driven modeling for the identification of the valve operation timings

3.1 Experimental setup

The experimental setup, as illustrated in Fig. 2, includes a gas cylinder containing nitrogen (1), two on-off valves (2,4), a pressure regulator (3), an absolute pressure transducer (Kulite HEM 375-100A) (5) with a total error band of ± 0.1% of its full-scale output, a pressure vessel (24 liter) (6), a pilot-operated hung-type diaphragm valve that was tested (7), an electronic circuit to drive the valve (8) and a push-button to activate the valve (9). The setup also includes a data acquisition system consisting of a NI-6120 model data acquisition card (National Instruments) mounted on a personal computer, which sampled data at 40,000 samples per second.

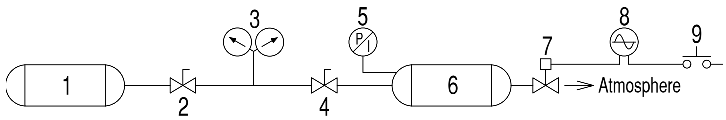

Figure 2: Schematics of the experimental setup: (1) Gas cylinder, (2) on-off valve, (3) pressure regulator, (4) on-off valve, (5) absolute pressure transducer, (6) pressure vessel, (7) pilot-operated hung-type diaphragm valve, (8) electronic circuit, (9) push-button.

The purpose of the experiment is to measure the temporal changes in pressure within the pressure vessel. Pressure readings were obtained for 19 case studies encompassing a differential pressure range of 69 to 487 kPa. In each test, the pressure vessel was filled to a certain pressure level using a gas cylinder which contains nitrogen. Following an equilibration period for each test, the push button was used to trigger the electronic circuit, which supplies alternating current to the coil of the valve for a preset time, and the pressure transducer measured the pressure change within the vessel in real time as the gas was released into the atmosphere.

3.2 Mathematical modeling of time-dependent pressure and area: Utilizing experimental data to identify model parameters

A mathematical model was formulated to simulate the time-dependent changes in pressure and temperature within a pressure vessel with a constant volume during the release of gas. This model relies on the application of the laws of conservation of energy and mass, along with the ideal gas equation of state, resulting in the differential equations given as Eq. (1) and Eq. (2).

$$\frac{dT}{dt} = -\frac{rT}{Vp}\dot{m}(T\kappa - T), \tag{1}$$

$$\frac{dp}{dt} = -\frac{\kappa r}{V}\dot{m}T. \tag{2}$$

In these expressions, the variables p and T represent the instantaneous pressure and temperature inside the pressure vessel, respectively, while V denotes the volume of the pressure vessel. Furthermore, r and κ refers to the specific gas constant and the heat capacity ratio, respectively.

Assuming the valve as a nozzle, the mass flow rate is expressed by Eq. (3), derived from White [6], where p_{a} denotes the ambient pressure. This equation considers the inlet pressures of the nozzle, both above and below the critical pressure, defined as p_{cr}, as seen in (4).

$$\dot{m} = \begin{cases} p\left(\frac{p_{\mathrm{a}}}{p}\right)^{1/\kappa} A\sqrt{\frac{2\kappa}{(\kappa-1)rT}\left[1-\left(\frac{p_{\mathrm{a}}}{p}\right)^{\kappa-1/\kappa}\right]}, & \text{if} \quad p_{\mathrm{a}}/p \geq p_{\mathrm{cr}}, \quad \text{(a)} \\ p\, {p_{\mathrm{cr}}}^{1/\kappa} A\sqrt{\frac{2\kappa}{(\kappa-1)rT}\left[1-(p_{\mathrm{cr}})^{\kappa-1/\kappa}\right]}, & \text{if} \quad p_{\mathrm{a}}/p < p_{\mathrm{cr}}, \quad \text{(b)} \end{cases} \tag{3}$$

$$p_{\mathrm{cr}} = \left(\frac{2}{\kappa+1}\right)^{\kappa/\kappa-1}. \tag{4}$$

The effective flow area of the valve is defined as a piecewise linear function based on event timings in order to provide a time-dependent expression, which is essential for analyzing the dynamic characteristics of the valve. The mathematical expression of the effective flow area (A) is given in Eq. (5).

$$A = \begin{cases} 0, & \text{if} \quad t < C_2, \quad \text{(a)} \\ C_1(t - C_2), & \text{if} \quad t < C_3, \quad \text{(b)} \\ A_{\max}, & \text{if} \quad t < C_4, \quad \text{(c)} \\ A_{\max} - C_6(t - C_4), & \text{if} \quad t < C_5, \quad \text{(d)} \\ 0, & \text{if} \quad t > C_5. \quad \text{(e)} \end{cases} \tag{5}$$

The maximal effective area $A_{\max}$ and the slope C_6 are related to other parameters through relations (6) and (7), respectively.

$$A_{\max} = C_1(C_3 - C_2), \tag{6}$$

$$C_6 = A_{\max}/(C_5 - C_4). \tag{7}$$

The primary event timings are defined as follows: opening start (t_{os}), fully open (t_{fo}), closing start (t_{cs}), and fully closed (t_{fc}). These timings correspond to the variables C_2 through C_5 in Eq. (5), while C_1 and C_6 represent the opening and closing slopes, respectively.

Differential equations (1) and (2) were solved numerically using MATLAB®, with initial guesses for the parameters taken from C_1 to C_5.

In order to identify the parameters for the mathematical model, the Nelder-Mead method, a direct search optimization algorithm, was employed due to its effectiveness in complex systems where gradient computation is impractical. The algorithm employs an iterative process of refinement, whereby the simplex is evaluated and adjusted at each vertex through reflection, contraction, or expansion. This is done with the objective of minimizing the mean squared error described in Eq. (8), thereby ensuring alignment between the model predictions and the experimental findings.

$$\min = \frac{1}{n} \sum_{i=1}^{n} (P_{\text{exp}} - P_{\text{sim}})^2 \tag{8}$$

The residual root-mean-square error ranges from 0.3 kPa for the lowest differential pressures to 1.3 kPa for the highest differential pressures. These values mostly reflect the random scatter of the pressure signals.

4 Results and discussions

This section presents the findings of the study on the dynamic behavior of pilot-operated hung-type diaphragm valves. The variation of effective flow area (A_{eff}) in the valve, the variation of absolute pressure in the vessel, as determined by experimentation (P_{exp}) and simulation (P_{sim}), and the variation of electrical current-which is scaled 150 times up for visualization purpose- (I_{v}) drawn by the valve are represented in Fig. 3 for the case of an initial vessel absolute pressure of 584 kPa. The driving current line has been scaled up to better illustrate the details.

The four principal timings, which represent the sequence of events in the operation of the valve, are illustrated in Fig. 3. These include the opening start (t_{os}), the fully open (t_{fo}), the closing start (t_{cs}), and the fully closed (t_{fc}).

4.1 Opening and closing behavior: Analysis and assessment

The examination of valve dynamics can be divided into two fundamental sets of parameters. The first set pertains to the opening response, which includes the opening delay (t_{od}), the time required for the valve to begin opening; the opening time (t_{ot}), the duration to achieve maximum opening; and the total opening response time (t_{or}).

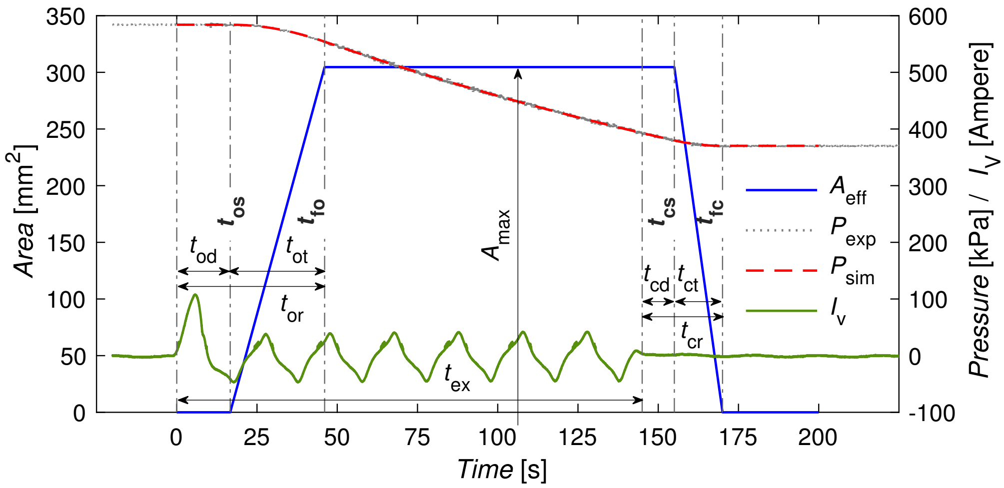

Figure 3: The graphical representation of the solution for an initial pressure of 584 kPa: The key temporal characteristics of the valve response include the opening phase, which consists of the opening delay (t_{od}), opening time (t_{ot}), and opening response (t_{or}=t_{od}+t_{ot}); and the closing phase, identified by the closing delay (t_{cd}), closing time (t_{ct}), and closing response (t_{cr}=t_{cd}+t_{ct}). The excitation duration (t_{ex}) is also important to understanding the dynamics. The value of A_{max} indicates that the valve has reached its maximum flow area.

The second set relates to the closing response, encompassing the closing delay (t_{cd}), the time necessary to commence closing; the closing time (t_{ct}), required to attain complete closure; and the cumulative closing response time (t_{cr}). These parameters are presented in Fig. 4 across the pressure range for an excitation duration (t_{ex}) of 137 ms.

In the horizontal axis of Fig. 4, the pressure differential for both the opening and closing responses is defined as the difference between the vessel pressure—either at the start of actuation or at the beginning of valve closing—and the ambient atmospheric pressure.

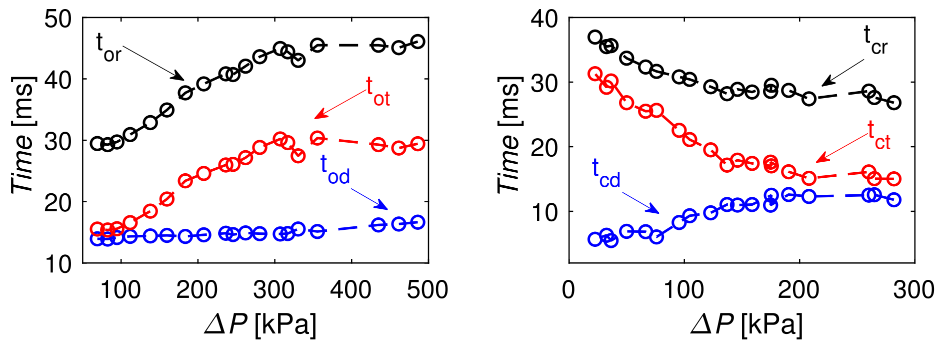

Figure 4: Opening (a) and closing (b) responses of the pilot-operated hung-type solenoid valve across pressure differentials ranging from 69 kPa to 487 kPa and 22 kPa to 282 kPa, respectively.

Opening delay (t_{od}) demonstrates a linear increasing trend across the entire pressure range, with a difference between highest and lowest values is 2.7 ms. The opening time (t_{ot}) correlates closely with the opening response (t_{or}), with the fastest recorded opening time of 15.3 ms at a pressure difference of 82.5 kPa, and the slowest at 30.3 ms at 355.5 kPa. The opening response (t_{or}) slows down almost linearly until reaching 355.5 kPa pressure difference, after which it approaches a limit. The valve reaches its maximum open state in 29.2 ms at the fastest and 46.1 ms at the slowest where pressure differences at lowest.

As the pressure differential increases, distinct effects on the valve's closing and opening dynamics emerge. During the closing phase, higher pressure generates additional force on the diaphragm, enhancing the downward force from the plunger spring. This results in improved closing response (t_{cr}) and reduced closing time (t_{ct}). Conversely, in the opening phase, the increasing pressure differential leads to a worsening opening response (t_{or}) and extended opening time (t_{ot}). This is due to the longer time needed for force balance on the diaphragm to establish under high pressure differentials, characteristic of pilot-operated valves. At lower pressure differentials, the valve functions as a direct-acting valve, showing better timing characteristics.

The closing delay (t_{cd}) show an increase with increasing pressure. After difference pressure around 200 kPa, the behavior of the closing delay (t_{cd}), the closing response (t_{cr}) and time (t_{ct}) linearizes, reaching a limiting value. The fastest closing time was observed to be 15 ms at 281.8 kPa, while the slowest was 31.3 ms at 22.6 kPa. The best and worst values recorded for the closing response were 26.8 and 37 ms, respectively.

As illustrated in Figure 4(a), at 330 kPa, a deviation from the expected behavior occurs within the context of reproducibility, particularly with shorter excitation times that enhance dynamic interactions within the valve.

5 Conclusion

This study presents an analysis of the opening and closing behavior of pilot-controlled hung-type solenoid valves, with a particular focus on the critical parameters that influence their behavior. In light of the findings, it can be concluded that the valve is suitable for applications requiring a rapid response. Furthermore, the examined valve demonstrates consistent opening and closing times in response to varying differential pressures, indicating its reliability.

Due to their structural design, these valves exhibit superior opening response compared to conventional pilot-operated solenoid valves in low pressure differences, and demonstrate faster closing times than opening times. These findings underscore the necessity of precise knowledge of operating conditions, including the relative importance of each response and the pressure difference at which operation occurs. The effective parameters in both the opening and closing responses are the opening and closing times, respectively. This is due to the negligible delay times. Therefore, future efforts should focus on both parameters to enhance the opening and closing responses.

This indicates that further development may be achieved by focusing on the mechanical structure (design and materials) and moving components of the valve, with consideration given to fluid flow interaction rather than the electromagnetic component. Consequently, another avenue for future research could be the comprehensive examination of the impact of varying excitation durations on the dynamics of moving components.

Acknowledgment

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