COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION ON THE FLOW CHARACTERISTICS OF ELECTROPNEUMATIC VALVES

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Summary

A simplified one-dimensional (1D) simulation model has been elaborated in AMESim environment, which is capable for analyzing and predicting the flow characteristics of small electropneumatic (EP) valves within a wide range of pressure ratios in the sonic range. The flow coefficient in the model has been identified on the basis of experiments and was compared with the Perry model. The flow coefficient values have been successfully reproduced by axisymmetric quasi-3D (Q3D) computations using the FLUENT code.

1 INTRODUCTION

Electropneumatic (EP) valves are widely applied in several areas of industry. The knowledge on the dynamic flow characteristics of such valves is especially important in the cases when they are integrated in fast-response, controlled fluid power systems as control devices. A typical application of this kind is realization of control functions in intelligent EP braking systems of motor vehicles. The dynamic flow characteristics of EP valves influence the successful operation of the entire fluid power equipment.

As illustrated in SZENTE et al. [5], a simplified 1D simulation tool can be effectively used in design, research and development regarding controlled fluid power systems. The EP valve models integrated in such models must represent reliably the transmission characteristics of the EP valve, without time-consuming and practically unnecessary resolution of 3D effects.

This paper presents an advanced 1D fluid mechanical submodel prepared in AMESim environment, supplying reliable information on the flow transmission characteristics of the EP valve. The 1D model has been parameterized by experiments carried out on an EP valve of case study. The flow transmission characteristics identified experimentally were compared with literature data and have been successfully resolved by axisymmetric Q3D flow computation using code Fluent.

2 EP VALVE AND TEST CASE

The valve under investigation is applied in fast-response pneumatic systems as control valve providing e.g. pressure signal for relay valves. Such miniature valves must provide rapid, pulsed fluid transmission between enclosures of relative pressures in the order of
magnitudes of 10 bar and 0 bar within a time period in the order of magnitude of 0.01 s. It is of critical importance to elaborate a reliable fluid dynamical model for the valve to be applied in design of the fluid power hardware and its control.

Fig. 1 shows the simplified scheme of the valve (SZENTE and VAD [6]). The valve body position coordinate $x$ is also indicated in the figure. The valve body is equipped with flexible seal and contact surfaces. In absence of solenoid excitation, the valve body is kept at its closed end-position by the return spring. The solenoid is energized by DC voltage. The frame and the jacket assist in development of a magnetic circuit. The resultant magnetic force displaces the valve body against the return spring. As a consequence, a flow cross-section develops through the orifice.

In order to investigate experimentally the flow transmission characteristics of the EP valve under present investigation, a test facility has been set up. The scheme of the test system is shown in Fig. 2. It comprises two pneumatic chambers and the valve described above. At the beginning of each case, the large chamber has been pressurized while the small one has been set to atmospheric pressure. By setting the pressure in the large chamber, various pressure ratios (downstream to upstream absolute pressure) have been adjusted to initialize the experiment. Then the valve has been opened and the small chamber has been loaded with the pressurized air from the large chamber. The pressure and temperature in the large chamber stayed practically constant during the loading process. Pressure transducers have been incorporated to both chambers. No temperature measurement was applied on the small chamber.

Fig. 2. Scheme of the test system and its AMESim representation
3 1D VALVE MODEL AND EXPERIMENTAL PARAMETER IDENTIFICATION

The through-flow area of the EP valve has been modeled as a pneumatic orifice with a geometrical cross-section controlled by the valve body position. The flow through the valve has been approached as series of short-term stationary sub-processes. The mass flow rate \( q_m \) through the orifice is a function of upstream absolute pressure \( p_{up} \), upstream temperature \( T_{up} \), orifice cross-section \( A \), flow coefficient \( C_q \) and mass flow parameter \( C_m \) ([2], BIDEAUX and SCAVARDA [3]):

\[
q_m = A \cdot C_q \cdot C_m \cdot \frac{p_{up}}{\sqrt{T_{up}}}
\]  

(1)

The experimental set-up has been represented in AMESim environment [4], making possible 1D dynamic flow simulation (Fig. 2). No heat transfer is considered in the simulation model of the small chamber. The quantities in Eq. (1), except for \( C_q \), have been set according to the geometrical and measurement circumstances. Considering that the effect of heat transfer is negligible only at the initial time instance of the loading process, the initial rate of pressure increase in the small chamber was considered as a basis of experiment-based calculation of mass flow rate. The value of \( C_q \) has been selected in such a way that the initial rate of simulated pressure increase in the small chamber is equal to that experienced in the measurements, representing that the initial sonic mass flow rate (i.e. the left-hand side of Eq. (1)) is equal for the measured and simulated cases. Comparative sample data for measured and simulated pressures in the small chamber are shown in Fig. 3. Except for the initial period immediately after opening the EP valve (where the effect of heat transfer through the chamber wall is negligible), a minor departure can be observed between measured and simulated pressure values due to heat exchange between the small chamber and the environment.

Using the above described procedure, a pressure ratio-dependent \( C_q \) parameter has been established experimentally for the 1D model. The experimental results of \( C_q \) have compared to data according to values according to the Perry polynomial established for sharp-edged orifices (McCLOY and MARTIN [1]). The results are presented in Fig. 6 and will be discussed later.

![Fig. 3. Small chamber sample pressure comparison diagrams](image-url)

4 Q3D SIMULATION MODEL AND SIMULATION
The experimentally determined $C_q$ values built in the 1D AMESim model were attempted to be reproduced by axisymmetric Q3D computations using Computational Fluid Dynamics (CFD) code FLUENT [7]. Because of axial symmetry, the 3D valve model has been transformed to Q3D axisymmetric domain. Fig. 4a shows the 3D layout of the valve, while Fig. 4b shows the 2D scheme that has been used in CFD simulation. Because of present limitations in the 3D simulation software available, the movement of the valve body has not been incorporated into the model.

![3D valve layout](image)

**Fig. 4a.** 3D valve layout

![Q3D scheme](image)

**Fig. 4b.** Q3D scheme

The simulation software computed the mass flow rate for the initial state, the cross-section of the flow has been given. $p_{up}$, $p_{down}$ and $T_{up}$ have been given as boundary conditions. Three computed Mach number contour distributions can be seen in Fig. 5 as examples. Such diagrams will be used in the future for a detailed analysis of flow field within the valve. Considering that $C_m$ is constant through the sub-critical pressure ratio domain (sonic flow, BIDEAUX and SCAVARDA [3]), the value of $C_q$ has been extracted from the CFD simulation using Eq. (1) and has been compared to the experimental results and the Perry model in Fig. 6.

![Mach contour plots](image)

**Fig. 5.** Mach contour plots at pressure ratios of $p_{down}/p_{up} = 1:10$, $1:5$ and $1:2.5$
5 DISCUSSION OF RESULTS

Fig. 6 shows that, contrary to the Perry model, $C_q$ is practically constant within the sonic range, as the experiment-based data built in the 1D AMESim model show. To explore the reasons of departure is a subject of future work. The measurement results show that the simple 1D model derived from Eq. (1) can be effectively used for simulation of this EP valve with a constant $C_q$ value of 0.74. This value is the same as the one that can be computed from the Perry polynomial for the critical pressure ratio of 0.53. Nevertheless, at smaller pressure ratios the difference between the Perry model and the measurement increases continuously. The constant $C_q$ tendency has been properly resolved by the FLUENT Q3D computations. The $C_q$ value computed from the Q3D model is approximately 0.8, so the relative difference between the Q3D model and the measurement is about 8%. Possible causes of this deviation are the geometrical simplification, the measurement uncertainties and the residual errors from the discretization.

Based on the above, it is stated that the FLUENT Q3D results resolve the 1D measurement data qualitatively and, within a certain tolerance, quantitatively as well. Therefore, the FLUENT software is expected to be used reliably in future analysis of EP valve characteristics.

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REFERENCES