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MASS FLOW RATE CHARACTERISTIC OF THE FLAPPER-NOZZLE PNEUMATIC VALVE

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Abstract: Flapper-nozzle type valve is commonly used for precision, flow control in pneumatic systems. For the purpose of analysis and design the paper is concerned with nonlinear mass flow rate of the valve taking into account different flow regimes. Flow rate is static, nonlinear function and could not be solved in analytical form. In this paper Particle Swarm Optimization method is used for numerical solution. Depending on supply pressure and flow area ratio along the static characteristic different segment can be observed.
Keywords: flapper-nozzle valve, mass flow rate characteristic, PSO optimization method

INTRODUCTION

Pneumatic servosystems are widely used in industrial applications because of the favourable performances/price ratio. However, high accuracy control of such systems is difficult due to their complex physical nature [1]. In order to solve the problem of design and control of such systems, it is necessary to have better understanding of their nonlinear characteristics. A mathematical model which should clarify the most relevant static and dynamic behaviour of the pneumatic system is used for that purpose.

Flapper-nozzle type valves are frequently used in pneumatic systems because of their simple structure, high precision, sensitivity and a broad bandwidth. They are usually used in control devices or measurement instruments. Different models of these valves can be encountered in the literature: starting from linearized algebraic equations to nonlinear dynamic models [2,3]. The paper analyzes the mass flow rate nonlinearity of the pneumatic flapper-nozzle type valve with high supply pressure. Various flow regimes are analyzed because when the supply pressure is higher than 0.15 [MPa], the air compressibility must be taken into consideration.

MASS FLOW RATE CHARACTERISTIC

Figure 1 presents the functional scheme of the pneumatic system which will be analyzed in the paper. The system consists of a valve and a chamber (Ch). The valve consists of a fixed orifice-type restriction (Or) and a flapper-nozzle combination ($Fl-N_z$). By rotating the flapper about the pivot P_v, the nozzle flow area (A_{en}), i.e. the mass flow rate $\dot{M}_n$ changes. As a result, there occurs a change of the pressure P at the control port. Hence, the valve is treated as a displacement-to-pressure transducer. As previously mentioned in this paper, the input signal is the nozzle flow area (A_{en}). This paper deals with the static, nonlinear mass flow rate characteristic of the valve. A detailed mathematical description of the flapper-nozzle type pneumatic servo valve with four ports can be found in [2, 3].

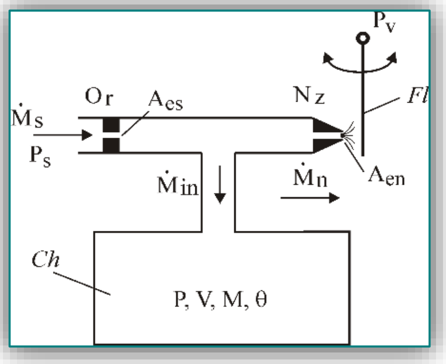


Figure 1. Pneumatic flapper-nozzle with the load chamber

The mass flow rate through the restriction can be in sonic or subsonic conditions depending upon the ratio of upstream-downstream pressure. According to the standard theory [4], it can be presented in the form:

$$\dot{M} = A_e \varphi(P_u, P_d, \theta_u) \quad (1)$$

The effective area of restriction A_e depends on the geometry of the flow area of the restriction and the discharge coefficient. Function φ depend on flow regime. If the downstream to upstream pressure ratio is smaller than a critical value P_{cr} (0.528 for air), the flow is sonic and the φ is linear function of upstream pressure. If the pressure ratio is higher than P_{cr}, the flow is subsonic and the φ depends nonlinearly on both pressures [4].

For a given flow area (A_{es}), and if holds $\theta = \theta_s = \theta_a = const.$ the mass flow rate through the fixed orifice depends only on the supply pressure (P_s) and the operating pressure P $(P_a \le P \le P_s)$. Figure 2 graphically presents that dependence.

All until $P/P_s \le P_{cr}$ (sonic regime), the flow has a constant value for the given P_s. Notice that the higher the P_s, the wider the area in which the flow rate has a constant value. For $P_{cr} < P/P_s \le 1$ (subsonic regime), the flow rate is a nonlinear function of the pressure P.

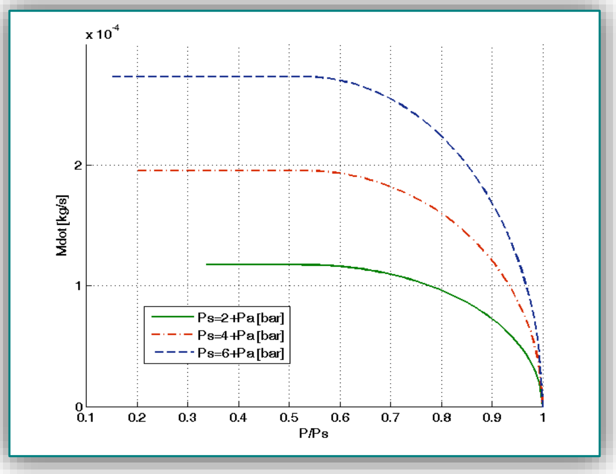


Figure 2. Mass flow rate through the fixed orifice

The mass flow rate through the nozzle, for a given P_s, depends both on the flow area A_e and the operating pressure P. Figure 3a and Figure 3b show those dependences respectively. For a given P, the flow through the nozzle is a linear function of the flow area regardless of the flow regime. The slope $\Delta\dot{M}_n / \Delta A_{en}$ increases with the increase of the operating pressure. It can be seen from Figure 3b that, in a general case, $\dot{M}_n$ is a nonlinear function of P. However, in the sonic regime ($P \ge P_a / P_{cr}$) the flow is, as in the fixed orifice, a linear function of the operating pressure.

In the steady state regime it can be written that:

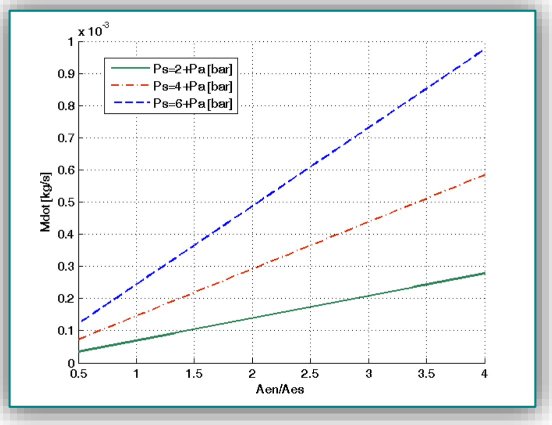
$$\dot{M}_{sN} = \dot{M}_{nN} = \dot{M}_N \qquad (2)$$

The mass of the fluid entering the chamber ($\dot{M}_{sN}$) is equal to the mass outflow through the nozzle ($\dot{M}_{nN}$). Based on (1), and (2), it follows that:

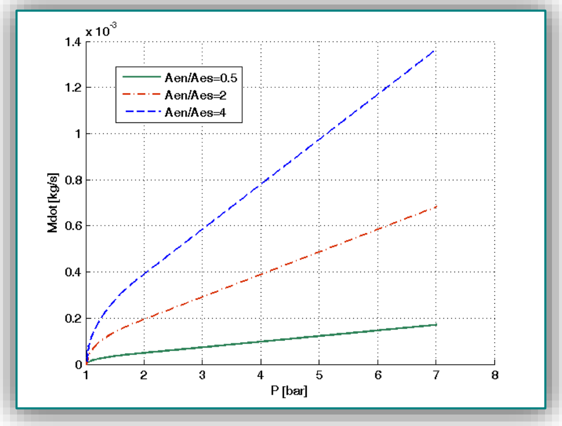
$$A_{es}\varphi(P_s, P_N, \theta_a) = A_{en}\varphi(P_N, P_a, \theta_a) \qquad (3)$$

The equation (3) could not be slolved analyticaly, in closed form. Unknown value for P_N we are looking for, depend on flow regime. On the other side, flow regime is determined by nominal pressure P_N.

Consequently we have to use numerical, iteration method. In this paper solution search is based on the Particle Swarm Optimization (PSO) method [5,6].



(a) depending on A_{en} / A_{es}



(b) depending on pressure P

Figure 3. Mass flow rate through nozzle

Figure 4 represents the algorithm of this method. Just as it is the case with all algorithms based on population, initial particle population is generated first. Position of the particle represents vector of parameters that are optimized: $x = (x_1, x_2, ..., x_n)$, or a potential solution. Random position in space which is explored, as well as initial velocities, is given to each particle. After that, the value of the objective function of each particle is determined, and that value is added to it as the best value for the particle in question, while the initial position becomes the best position of the particle P_{best}. When all the best values of particles are determined, the particle with the minimum value is searched, and its position becomes the best position for the entire swarm P_{gbest}. Afterwards, it is checked whether the criteria of optimization are satisfied, and if they are, the obtained results are displayed. If the criteria are not satisfied, new velocities and positions are to be calculated.

Figure 5 presents numerical solutions of equation (3). It shows the dependence of the operating pressure P_N on the ratio of flow areas for different values of supply pressure. It should be noted that the operating pressure in the nominal regime (2) is unambiguously determined by the ratio A_{en} / A_{es} and that it does not depend on the type of load with which the flapper-nozzle is connected. The transition process depends on the type of load, but the nominal values of pressure depend only on the flapper position. On each of the curves from Figure 5, except the curve designated by number 3, there are three segments. On the curve 3 there are two segments. The segments are defined by means of the points A and B. The point A is the point on the curve at which:

$$P_N / P_s = P_{cr} \tag{4a}$$

It is the operating point at which the flow regime at the fixed orifice changes. The point B is the point on the curve at which:

$$P_a / P_N = P_{cr} \tag{4b}$$

It is the operating point at which the flow regime at the nozzle changes. Three characteristic cases of mutual ratios of the points A and B should be noted.

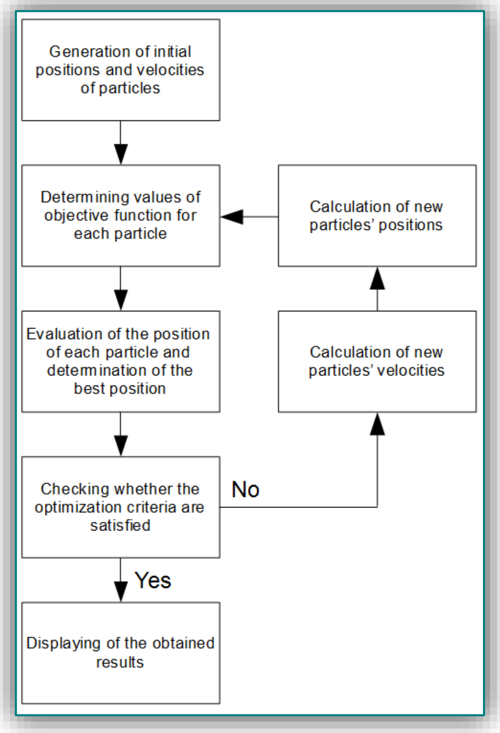


Figure 4. Algorithm of the method of particle swarm optimization

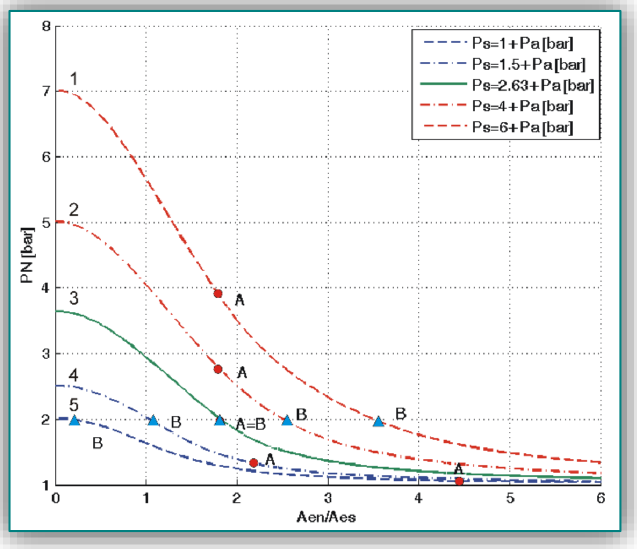


Figure 5. P_N - A_{en} / A_{es} relation in the nominal regime

CONCLUSION

Mass flow rate characteristic of the flapper-nozzle valve in steady state is a algebraic, nonlinear function of supply pressure and flow area ratio. In general case, it could not be solved in analytical form. Numerical method based on PSO algorithm represent a suitable tool for static analysis. For a given supply pressure there are three segments on flow rate characteristics: subsonic-sonic, sonic-sonic, sonic-subsonic. Width and order of these segments depends on ratio of nozzle flow area and fixed orifice flow area. Thus we can influence dynamic behavior of flapper-nozzle by choosing proper working point.

Nomenclature

$\dot{M}$ - mass flow rate through orifice [kg/s]
A_e - effective area of restriction [m2]
P - absolute pressure [Pa]
θ - temperature [K]

Subscripts

a - atmosphere
u - upstream
n - nozzle
d - downstream
s - supply
N - nominal operating regime

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Note

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