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Predictive model on the effect of restrictor on transfer function parameters on pneumatic control system

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Mathematical model was developed to monitor and predict the influence of restrictor or the characteristics of the functional parameters of the transfer function for pneumatic control system. The force acting from bellow is directly proportional to the effective cross-sectional area of the base which yielded extension of the bellow in both horizontal and vertical as well as its extension rate is dependent on the influence of the restrictor. The pneumatic controller represents the main force control operator in many industrial applications, where it's static and dynamic characteristics play an important role in the overall behavior of the control system, the total differential expression obtained in terms of restrictor pressure change per unit change in time was presented. The general solution equation established was resolved using the mathematical concept of laplace transformation as well as application of partial fraction which yields

$$PR(t) \quad = \quad p\left[1 + 2 - ce^{-t/c}\right]$$

The effect of the restrictor on the characteristics of the pressure was monitored, predicted and simulated using the MATLAB program approach. Result obtained reveals increase in restrictor pressure with increase in time. Restrictor pressure is influence by the capacitance, input pressure of bellow characteristics as well as other functional parameters.

Capsule Summary: The reliability on the transfer function parameters on pneumatic control system is influenced by the effect of restrictor. The reliability in terms of the bellow performance depends on the input pressure as well as the risk concept also depends on the horizontal and vertical compression and expansion. These characteristics determines the efficiency on the performance of the bellow on operational upon the influence of restrictor in the system.

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INTRODUCTION

Most of the earlier pneumatic control systems were used in the process control industries, where the low pressure air of the order 7 bar was easily obtained and give sufficiently fast response. In this case, the present of the restrictor will influence the fast response needed during the operational system output. This concept is a major problem to the electrical, chemical, mechanical and other aspect of engineering profession. Pneumatic control systems are machinery and in the field of automatic controllers. For instance, pneumatic circuits that convert the energy of compressed air into mechanical energy enjoy wide usage and various types of pneumatic controllers are found in industry (Humbird, 2009)

Certain performance characteristics such as fuel consumption, dynamic response and output stiffness can be compared for general types of pneumatic restrictor, such as piston cylinder 2000, Baranyi et al., 2004; Raven, 1987, Eckman 1958; Ogata, 19995). The final decision on the best type and design configuration for pneumatic restrictor can be made only in relation to the requirement of a particular application. The pneumatic restrictor has most often been of the piston cylinder type because of its how cost and simplicity (tabling et al., 1863). The pneumatic control power is converted to straight line reciprocating and rotary motions by pneumatic cylinders and pneumatic motors. The pneumatic control position servos system are used in numerous applications because of their ability to position loads with high dynamic response and to augment the force required moving the loads as revealed by some researchers (Humbird et al., 2010, Miroslaw and Ho, 2004).

Investigation conducted by Clements and Len, 1985 revealed that pneumatic systems are also very reliable. The open literature surveyed showed a wide spectrum of new applications of pneumatics errors such as milling machines, roboties and advanced train suspension (Humbird, 2009, Carter et al., 2003, Savkovic-Stevanoivc, 2007, 2006; Zaddeh, 1994).

The early detection of faults and other problems concerning the process are required. This detection is usually performed by using fault detection and diagnosis (FDD) methods implemented in a condition monitoring system. Condition-based maintenance as part of predictive maintenance is one of the tools used to increase productivity and reliability in the process industry. This is done by minimising unscheduled shutdowns and loss of product quality. Process plant performance and reliability cannot be improved without revealing deviations or problems by means of a condition monitoring system. This problem identification has to take place before problems become too serious in order to prevent major repairs and production breakdowns. Identification also has to take place online without disturbing the process, so as to maintain the efficiency of the plant. For this reason traditional offline performance tests are not feasible in real industrial applications these days.

MATERIAL AND METHODS

Pneumatic Proportional Control System

Consider the pneumatic system shown in Fig. 1. It consists of several pneumatic components. The components, which can be easily identified, are: flapper nozzle, amplifier, air relay, bellows and springs feedback arrangement etc. The overall arrangement is known as a pneumatic proportional controller. It acts as a controller in a pneumatic system generating output pressure proportional to the displacement e, at one end of the link. The principle of operation is goes thus. The input to the system is a small linear displacement e and the output is pressure P. The input displacement may be caused by a small differential pressure to a pair of bellows, or by a small current driving an electromagnetic unit. There are two springs K_2 and K_f those exert forces against the movements of the bellows A_2 and A? For a positive displacement of e (towards right) will cause decrease of pressure in the flapper nozzle. This will cause an upward movement of the bellows A_2 (decrease in y). Consequently the output pressure of the air relay will increase. The increase in output pressure will move the free end of the feedback bellows towards left, bringing in the gap between the flapper and nozzle to almost its original value. We will first develop the closed loop representation of the scheme and from there the input-output relationship will be worked out. The air is assumed to be impressible here.

The effect of pressure on the bellow expansion without restriction is shown in figure 2a whereas its impact of pressure on the bellow expansion with restriction is show in figure 2b.

The transfer function model formation

A lot of commercial pneumatic controller designs are based on the flapper nozzle principle. It is a very sensitive system, such that a small movement will cause the controlled pressure to change. The device uses bellows as transducer for converting pneumatic pressure to mechanical notion.

Assuming a force acting on the base simple bellow as shown in chapter two is AP where A is the effective cross-sectional area of the base, and the extension of the bellow is X. Therefore if the bellow is at rest

$$PA = rX0 \quad (1)$$

For the restriction bellow arrangement the rate of flow of air f through the restrictor R is given by the relationship.

$$f = \frac{P - P_1}{R} \quad (2)$$

assuming C to be the pneumatic capacitance of the bellow then

$$\frac{CdP_R}{dt} = P - P_R \quad (3)$$

$$\frac{CdP_R}{dt} = P_R = P \quad (4)$$

Application of Laplace transformation

$$\frac{dP_R}{dt} = SP_R(s) - P_R(0) \quad (5)$$

$P_R = P_R(s)$

$$P = P\ x\ \frac{1}{5} \quad (6)$$

$$C[SP_R(s) - P_R(0)] + P_R(s) = \frac{P}{S} \quad (7)$$

$$CSP_R(s) - CP_R(0) + P_R(s) = \frac{P}{S} \quad (8)$$

Because

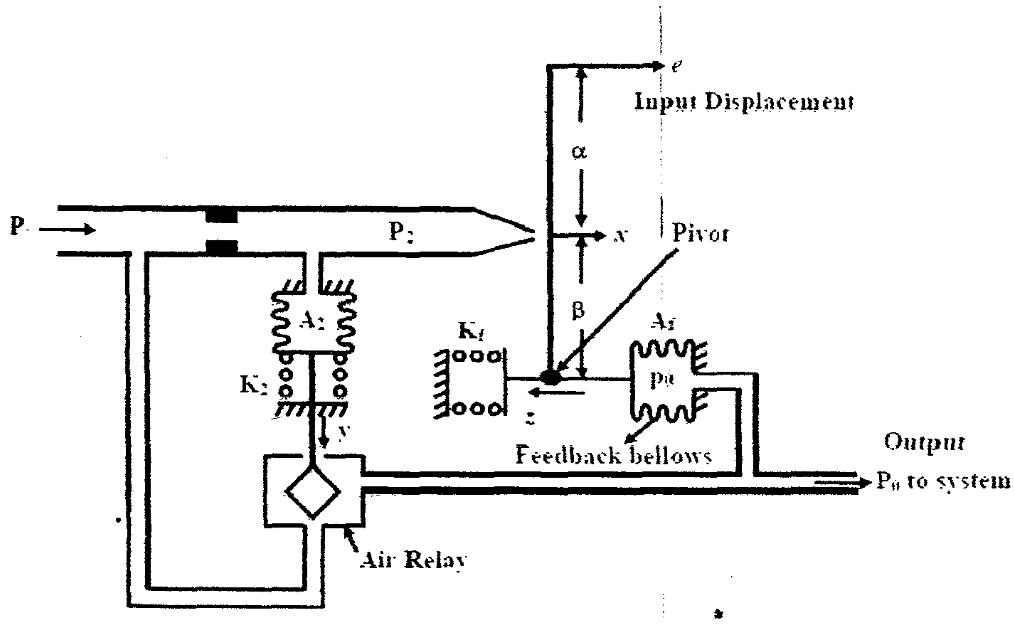

Fig. 1: A pneumatic proportional control

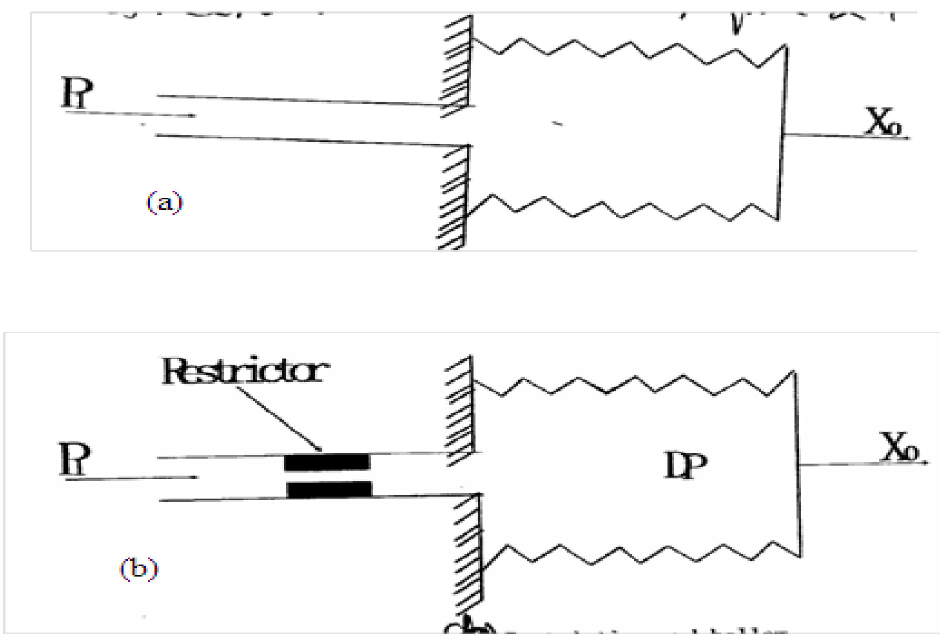

Fig. 2: A pneumatic proportional control action illustrating the effect of pressure on restriction and bellow characteristics.

$P_R\,(0) = 0$

$$CSP_R(s) + P_R(s) = \frac{P}{S} \qquad (9)$$

$$P_R s\ (CS + 1) = \frac{P}{S} \qquad (10)$$

$$PR(S) = \frac{P/S}{CS + 1}$$

$$PR(S) = \frac{P}{S}\ x\ \frac{1}{CS + 1}$$

$$PR(S) = \frac{P}{S(CS+1)} \qquad (11)$$

Applying both side by the LCM

1 = A(CS + 1) + BS

When S = 0

1 = A(0 + 1) + B (0)

A = 1

When S = -1

1 = A(-C + 1) – B

B = A + 1 – C

Where B = 1

B = 1 + 1 – C

B = 2 – C

$$\frac{1}{S(CS+1)} = \frac{1}{S} + \frac{2-C}{CS+1} \qquad (12)$$

$$CS + 1 = 0,\ CS = 1, S = -\frac{1}{C}$$

Therefore

$$PR(s) = P\left[\frac{1}{5} + \frac{2-C}{CS+1}\right]$$

$$PR(t) = P\left[1 + 2 - C\ e^{-\frac{t}{c}}\right] \qquad (13)$$

Model relationship between transfer function G and pressure without restrictor and with restrictor

Considering when

$C_1 = \dfrac{\partial Gs,O}{\partial PO,O}$ and $C_2 = \dfrac{\partial Gs,O}{\partial GO,O}$ (14)

$C_1 = \dfrac{\partial Gs,O}{\partial P0,o}$, $C_2 = \dfrac{\partial Gs,0}{\partial Pf,0}$ are the slop of the curve Gs versus Po and Gs versus Pf at the operating point. These values can be obtained either experimentally or from theoretical consideration.

In fact C1 = -C2 this can be ascertained from the fact that if Po and Pf both change from the operating point by the same amount (so that Po – Pf = 0), there is no change in the pressure drop and so there will also be no change in mass flow rate and Gs = 0. From equation (14) we obtain C1 = -C2 and equation (14) can be rewritten as

Gs = C1 (Po – Pf) (15)

Further, the pressure Pf inside the feedback bellows can also be obtained from expression

$$P_o = \frac{MRTf}{vf} \qquad (16)$$

Where

M = mass of the gas inside the bellows

V = volume of the gas inside the bellows

Tf = temperature of the gas (constant)

Let m and vf be the changes in mass of the gas and volume of the gas from the operating point corresponding change in pressure by Pf from the operating point.

From (10), one can also obtain the linearised expression around the operating point as

$$Po = \frac{\partial Pf,o}{\partial Mo}M + \frac{\partial Pf,o}{\partial Vf,o}Vf \qquad (17)$$

$= C_3M – C_4 V_f$ (18)

Where C_3 and C_4 are constants, the negative sign associated with C_4 is due to the fact that increase in volume causes decrease in pressure.

Now the change in volume inside the bellows is due to the displacement of the free end, and

Vf = AfZ (19)

Again the force balance condition at the feedback bellows gives

KfZ = PfAf

$$Pf = \frac{Kf}{Af}Z \qquad (20)$$

Equating (18) and (20) one can obtain

$$M = \frac{1}{C_3}\left[\frac{Kf}{Af} + C4\ Af\right]Z \qquad (21)$$

Differentiating the above equation, we have

$$gs = \frac{dm}{dt} = \frac{1}{C_3}\left[\frac{Kf}{Af} + C_4\ Af\right]\frac{dz}{dt} \qquad (22)$$

Again equating (15) and (22)

$$\frac{1}{C_1C_3}\left[\frac{Kf}{Af} + C_4\ Af\right]\frac{dz}{dt} = Po - Pf = Po - \frac{Kf}{Af}Z$$

From equation (20) we have

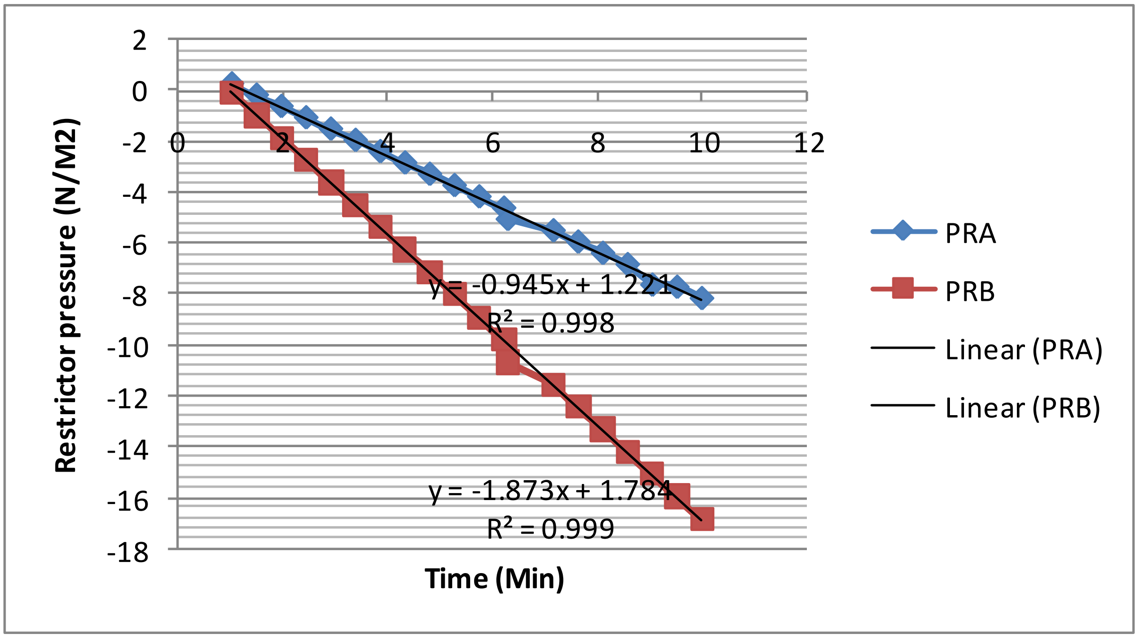

Fig. 3: Graph of restrictor pressure versus Time for component A and B

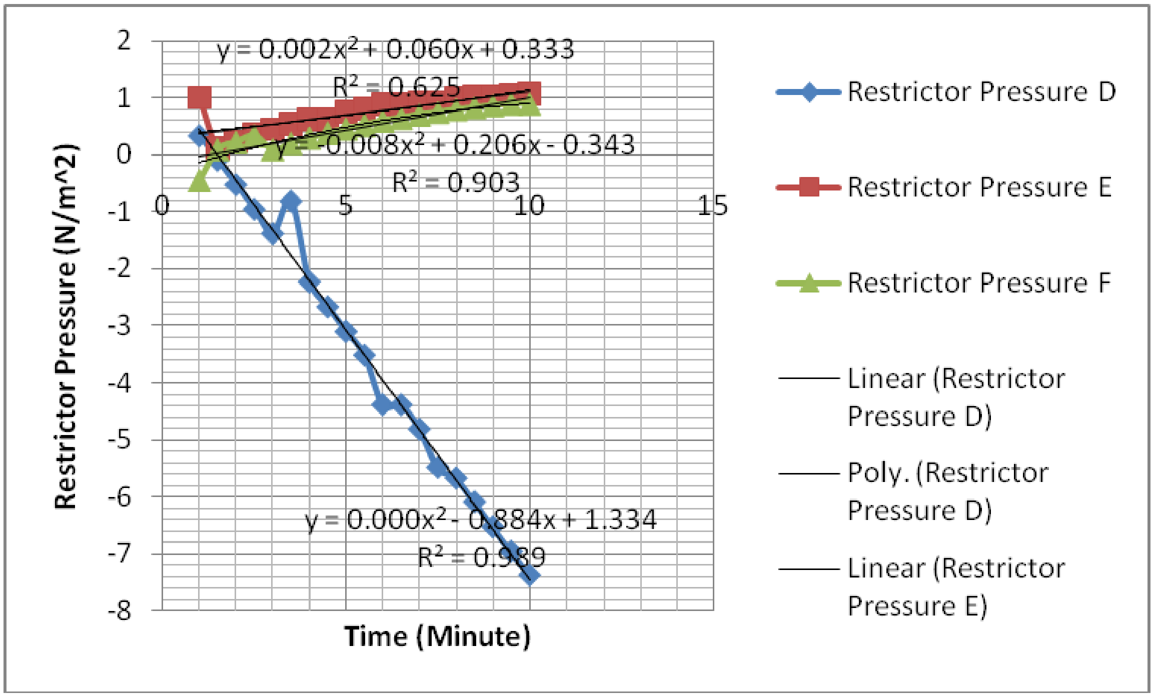

Fig. 4: Graph of restrictor pressure versus time for component D, E and F

$$\frac{Kf}{Af}\left[\frac{1}{C_1C_3}(1+\frac{C_4A^2f}{Kf})\frac{dz}{dt}+Z\right]=Po$$

It is clear that the introduction of the restrictor in the feedback bellows introduces a time constant in the feedback path.

Computational procedures

The following functional parameters were chosen to simulate the characteristics of the process as stated below

A. Condition A

Table 1: Computational evaluation on restriction pressure on the influence of different operational parameters

Time (mm)	Restrictor pressure NRA (N/m^2)	PRB (N/m^2)	Time (min)	PRD (N/m^2)	PRE	PRF N/m^2
1.0000	0.2654	-0.0691	1.0000	0.3402	-99461	-0.4375
1.4737	-0.1772	-0.9545	1.5000	-0.0898	0.1003	-0.2816
1.9474	-0.6199	-1.8399	2.0000	-0.5197	0.2296	-0.1406
2.4211	-1.0626	-2.7252	2.5000	-0.9496	0.3436	-0.0131
2.8947	-1.5053	-3.6106	3.0000	-1.3795	0.4442	0.1024
3.3684	-1.9480	-4.4960	3.5000	-1.8094	0.5330	0.2068
3.8421	-2.3907	-5.3814	4.0000	-2.2394	0.6114	0.3013
4.3158	-2.8334	-6.2667	4.5000	-2.6693	0.6114	0.3869
4.7895	-3.2761	-7.1521	5.0000	-3.0992	0.7416	0.4642
5.2632	-3.7187	-8.0374	5.5000	-3.5291	0.7955	0.5343
5.7368	-4.1614	-8.9229	6.5000	-4.3889	0.8849	0.5976
6.2105	-4.6041	-9.8082	6.5000	-4.3889	0.8849	0.6549
6.6842	-5.0468	-10.6936	7.0000	-4.8189	0.9220	0.7068
7.1579	-5.4895	-11.5790	7.5000	-5.2488	0.9546	0.7537
7.6316	-59322	-12.4644	8.0000	-5.6787	0.9835	0.7962
8.1053	-6.3749	-13.3497	8.5000	-6.1086	1.0089	0.8346
8.5789	-6.8175	-14.2351	9.0000	-6.5385	1.0314	0.8694
9.0526	-7.2602	-15.1205	9.5000	-6.968	1.0512	0.9009
9.5263	-7.7029	-16.0058	10.000	-7.3984	1.0687	0.9293
10.000	-8.1456	-16.8912				
	Condition A	Condition B		Condition D	Condition E	Condition F
	C = 3μF	C = 4μF		C = 3μF	C = 4μF	C = 5μF
	P = 0.4N/m^2	P = 0.6N/m^2	>>t(1,05,10)	P = 0.4 N/m^2	P = 0.4 N/m^2	P = 0.4 N/m^2
	t = 1-10min	t = 1-10min		t = 1-10 min	t = 1 – 10 min	t = 1 – 10 mins
>>t(1,10,20)					t = (1,0.5,10)	

C = 3μF

At t = 1 – 10 minute

P = 0.4 N/m^2

Using MATLAB to simulate

t = linspace (1, 10, 20);

P = 0.4;

p = P* (1 + 2 – 3* (3exp (- ¼)*t)

disp ([t' p'])

plot (t, p)

>> t = linspace (1, 10, 20);

>> p = 0.4;

>> p = P* (1 + 2 -3* (exp(-1/4)*t))

B: Condition B

C = 4μF

At t = 1 – 10 minute

P = 0.6 N/M^2

Using MATLAB to simulate

t = linspace (1, 10, 20);

P = 0.6;

p = P* (1 + 2 – 4* (exp (- ¼)*t))

disp ([t' p'])

plot (t,p)

D: Condition D

C = 4μF

P = 0.4 N/m^2

At t = 1 – 10 minute

>> t (1: 05: 10)'

E: Condition E

C = 4μf

P = 0.4 N/m^2

At t 1 – 10 mins

t = (1: 0.5 : 10)'

F: Condition F

C = 5μF

t = 1 – 10 (mins)

p = 0.4 N/M^2

Simulate

= (1: 0.5: 10)'

RESULTS AND DISCUSSION

The application of MATLAB 2013 model was applied to the developed model using the necessary functional parameters as stated above and the results obtained are presented in figures as well as the run out results from the MATLAB 2013 program module. Results for condition A is given in Table 1.

The result presented in Table 1 illustrates the pressure values due to restrictor influence on the flow characteristics of air into the bellow. The opposition pressure in the case is regarded as restriction pressure as well as in most cases the restrictor pressure is very small but with time increases for all cases considered during this investigation. As the capacitance and the input pressure varies its restriction pressure also varies. These variations in the restriction pressure can be attributed to variation in input pressure, capacitance and time.

From figure 3 it is seen that the restriction pressure decreases with increase in time. The variation is attributed to the variation in the time for computational procedure of A and B condition.

From figure 4 it is seen that the restriction pressure decreases for PRD and PRF whereas increase in PRE is observed with increase in time. The variation in the restriction pressure for PRD, PRF and PRE can be attribution in time, capacitance and input pressure.

CONCLUSIONS

The system provides a convenient method to control a non linear system by a non linear controller. It has been successfully to transfer function on pneumatic restrictor to establish the best discrete model to the system. In this case, a mathematical model was developed that describe the behavior of restrictor on a simple pneumatic control system. The result was obtained by implementing of equation in MATLAB 2013 software, from the characteristics of the result obtained after the model implementation revealed decrease in pressure due to the restrictor with increase in time for the pneumatic control system. This phenomenon illustrates the effect of restrictor in transfer functional characteristics of a pneumatic control system.

NOMENCLATURE

P_o, small differential pressure (N/m^2)
e, input displacement (M/s)
K_2 and K^f, springs that exert force against the bellow (N)
A_2 and A_f, area of the two bellow (m^2)
$X_{f,o}$, normal gap between flapper and the nozzle (m)
$P_{2,0}$, operating pressure (N/m^2)
X_f, incremental displacement (m)
P_2, change in pressure (N/m^2)
PD, proportional derivative
Gs, mass flowrate of the fluid (g/s^2)
M, mass of gas inside bellow (g)
V_f, volume of gas inside the bellow (m^3)
T_f, temperature of the gas constant (oc)
C_3 and C_4, constant
P, pneumatic
PR(s), pressure on the restrictor with laplace sign (N/m^2)
PR(t), change in restrictor pressure with respect to time domain (N/m^2/min)
dP_R, change in proportional derivative or restriction pressure (N/m^2)
C, capacitance (μF)

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