Investigation of Response Time Analysis of a Pneumatic Valve

Sarathdas S
M. Tech:
Machine Design
NCERC Pampady, Thrissur

Deepak K. P
Assistant Professor
Automobile Department
NCERC Pampady, India

Dr. K. Sentil Kumar
Head of Department
Automobile Department
NCERC Pampady, Thrissur

***Abstract*: This paper describes mathematical modeling and analysis of the opening of pilot operated solenoid valve. A series of cold gas thrusters for propellant settling and orientation control of stage before and after the main engine operation. The equations are derived and solved numerically. The mathematical model for electromagnetic and mechanical dynamics is derived by making some simplifying assumptions. It is shown that the behavior of valve in the opening processes. This makes the design complicate and prediction of valve response difficult in traditional methods. It is carrying out a mathematical model to predict the performance of the valve using MATLAB software.**

A discussion is presented with an explanation of the results and a Comparison of the analysis results with test results of the hardware developed.

I. INTRODUCTION

Solenoid valve is an integrated device actuated by the electro magnet, solenoid which actuates either a pneumatic or hydraulic valve. Solenoid refers to a coil of wire, often covered around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoid valve is an electromechanical valve for use with liquid or gas and is controlled by an electric current through a solenoid coil.

The term solenoid valve is referred to any valve device actuated by the electromagnet. It essentially consists of a valving element with a poppet, seat, spring etc and an actuator portion consisting of the solenoid coil and armature which is connected to the valve poppet which controls the flow. Basic principle behind the functioning of a solenoid valve is that when an electric current is passed through the coil, it produces a magnetic field in the axial direction which attracts the spring loaded piston and thus, opens the fluid flow. Solenoid valves may be classified as;

- Direct acting solenoid valves
- Pilot operated solenoid valves

Pilot Operated Solenoid Valve vs. Direct Acting Solenoid Valve

Main advantage of usingthe pilot operated solenoid valve is that they reduce the valve weight and minimize the power requirements. Pilot operated solenoid valves are employed in order to contain size and weight while handling high flows. Pilot valves require much less power to control, but they are noticeably slower. Pilots may be designed for modulating opening or closing action. Whereas a direct acting solenoid valve may only need full power for a short period of time to open it, and only low power to hold it. Pilot operated solenoid valves has to operate for a very long time necessitating continuous power drain, which would otherwise require a much larger force to operate.

II THEORY

A. *Description of Thruster Valve:*

The thruster is an integrated assembly of a pilot operated solenoid valve and flow nozzle. While the valve portion remains same for both 15N and 5 N thrusters, the nozzle functional dimensions may vary for each thruster to get the specified thrust. The valve portion comprises a main valve with soft on hard flat poppet and a pilot valve also with soft on hard flat poppet. The pilot poppet is housed inside the inner cavity of the main poppet and both are normally kept closed by combined load of spring and unbalanced pressure loads. This shall ensure the required the leak tightness of the main and pilot valves.

Working principle:

On energisation of the solenoid coil,[1] the pilot valve opens due to the magnetic force of attraction between the solenoid plunger (which is the integral part of the pilot valve poppet) and armature. Since, the pilot valve port is small, the required load and thereby, the plunger diameter, number of coil ampere turns and power are less compared to a direct acting solenoid valve with a port equal to that of main valve .

When the pilot valve opens, the gas in the main valve poppet cavity is discharged to the nozzle through the pilot valve port, in turn, causing a differential pressure across the main poppet. Since, the orifice size (0.4 mm) feeding the main valve poppet cavity is smaller than the pilot valve port, the differential pressure across the main poppet is continuously maintained. The main poppet now opens under the influence of this differential pressure and fluid flow takes place to the nozzle.

On de-energisation of the solenoid coil, the poppet valve closes initially, followed by the closure of the main valve.

III METHODOLOGY AND PROCEDURES

Division of Functions

When the valve is operated by giving electrical command of 28VDC, the pressure rise at the valve outlet and thereby thrust at nozzle outlet is developed with a delay, called as the valve opening response. This time is critical for the mission as it determines the impulse bit for a thruster specified operating time. The entire delay in the response of the OSS thruster valve can be divided into the following modules: 1.Electrical delay, 2.Dynamic analysis of pilot poppet, 3. Variation of pressure force acting on the main poppet, 4. Dynamic analysis of main poppet.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 07, July-2016

Module 1:

Electrical delay: The time from the start of giving electrical command and to reach the required magnetsing force/ max. Current.

Table 1 input for module 1

Sl. No.	Description	Value
1	μ_o – Permeability of air	$4\pi \times 10^{-7}$ H/m
2	N- No. of turns of the coil	1630
3	I_{max} – Max. coli current	0.3 A
4	R – resistance of the coil	90 Ω
5	L – inductance of the coil	0.257 H
6	A – effective area of the plunger	50×10^{-6} m^2
7	l – air gap length	0.5mm
8	t-time step	0.001 to 1 sec

Findoutthemagnetic forcé of everyinstant of time, themagnetic forcé equation as shownbelow

$$F = \mu_o N^2A/2l^2 \times (I_{max}\times(1 - e^{(-Rt/L)}))^2$$

Aftersubstitution of thevalues of inputs availablewehavetheequation of the forcé varyingwiththe time as givenbelow

$$F = (4\pi \times 10^{-7}\times 1630^2\times 50\times 10^{-6}\times 0.3^{2)} \times (1\text{-}e^{(-90\times t/0.257)})^2 / (2\times 0.5^2\times 10^{-6})$$

ThereforeAftersimplificationweget

$$F = 30.033\times (1\text{-}e^{(-350.194t)})^2$$

Module 2:

Dynamic analysis of pilot poppet: The time delay for the pilot poppet to start and reach its full specified stroke.

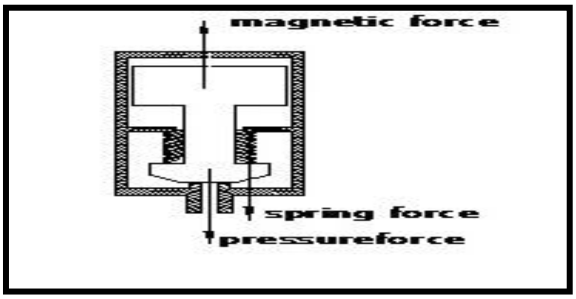


Fig 1: Schematic of pilot valve

Table 2 input for module 2

Sl. No.	Description	Value
1	Fs– Assembled spring load	7.4 N
2	Ksp- Stiffness of the pilot spring	4.4145 N/mm
3	P_2– Pressure acting above the pilot poppet	2.8 N/mm^2
4	P_3 – Pressure acting outside the valve	0.1 N/mm^2
5	L – sealing area for pilot poppet	0.3848 mm^2
6	mmp – mass of the moving parts in the pilot poppet	0.0085 kg
7	Lmaxpp– Maximum lift of the pilot poppet	0.2 mm

There are pressure force, spring force and the magnetic force acting on the system, out of which, the pressure force and the spring force are acting in the downward direction and are trying to keep the valve closed and the magnetic force is the one which is responsible for the opening of the valve and is acting in the upward direction. Till the time, the magnetic force of attraction is less than the sum of spring force and pressure force; valve would remain closed as the net force acting on the system would be acting in the downward direction only. At the instant, magnetic force exceeds the sum of the other two forces, there would be net upward force acting on the system and the pilot valve would start moving up under this net resultant force which is nothing but the difference of magnetic force and the sum of pressure force and spring force. The maximum lift of the pilot poppet is limited to 0.2 mm

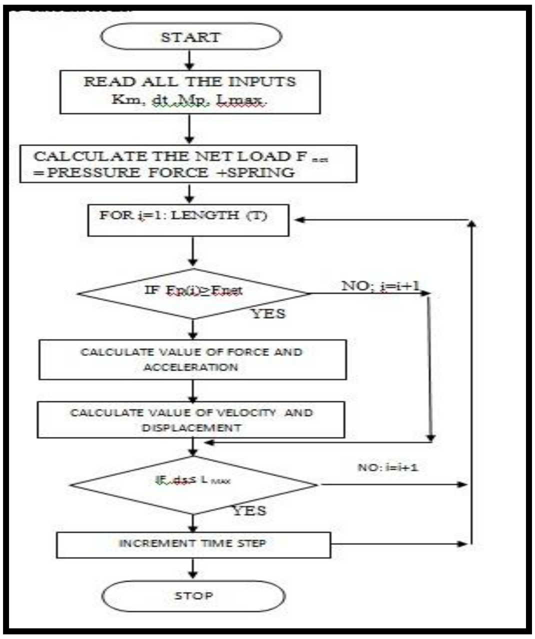
Acceleration of the pilot poppet will be this average force divided by the mass of the moving parts in the pilot poppet.

Now, the velocity at any time t can be calculated from the basic kinematic equation i.e.

v = u + at which can be written for the time interval dt as

Again, lift of the pilot poppet in this time interval dt is calculated according to the equation $s=ut + ½ at^2$.

Flow chart for calculations:



International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 07, July-2016

Module 3:

Variation of pressure force acting on the main poppet; Time delay to reach the opening unbalanced pressure force on main poppet.Mainly determined by the feeding orifice and pilot valve poppet travel.

Table 3 input for module 3

SL no	Description of inputs	Values
1	Γ-Ratio of specific heats of N_2 gas	1.4
2	P3-Pressure at sink	0.1 N/mm^2
3	P2-Initial pressure in chamber 2	2.8 N/mm^2
4	Rg-Gas constant for N_2 gas	$296.93x10^3$ N.mm/kg.K
5	T2-Initial temperature in chamber 2	300 K
6	Cd_{23}-Discharge coefficient chamber 2 to 3	0.8
7	A_{23}-Area of the orifice connecting chamber 2 to 3	0.38485 mm^2
8	V_2-Volume of chamber 2	1516.23 mm^3
9	T_1-Temperature chamber 1	300 K
10	Cd_{12}-Discharge coefficient in orifice connection chamber 1 to chamber2	0.8
11	A_{12}-Area of the orifice connecting chamber1 to 2	0.12566 mm^2

Now let us consider a tank of infinite volume, which means even if we vent the tank, its pressure P0 is not going to decrease. Hence P0, and ρo is constant. In such case the flow rate m_{act} is proportional only to the pressure ratio i.e. outlet pressure P1 and area of orifice.

If pressure ratio R=1 i.e. P1=P0, there will be no mass flow. But as the valve pressure at P1 is lowered R value becomes less and flow starts and with further lowering of P1 value mass flow rate increases till it reaches a maximum value. After this maximum value the mass flow rate doesn't increases even if the pressure ratio is further reduced. This constant mass flow rate is called critical mass flow rate and the pressure for this condition is called critical pressure ratio. At this critical pressure flow is choked flow i.e. mass flow rate is Maximum.

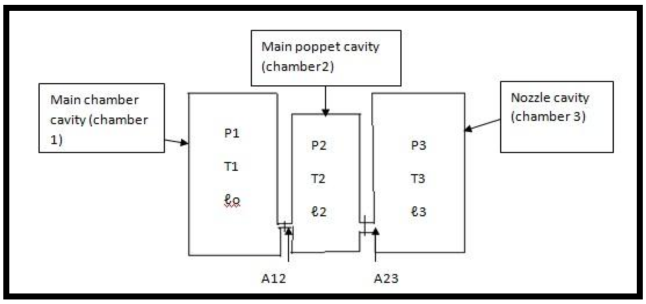


Fig 2: Schematic for pneumatic delay

For non choked condition mass flow rate through orifice:

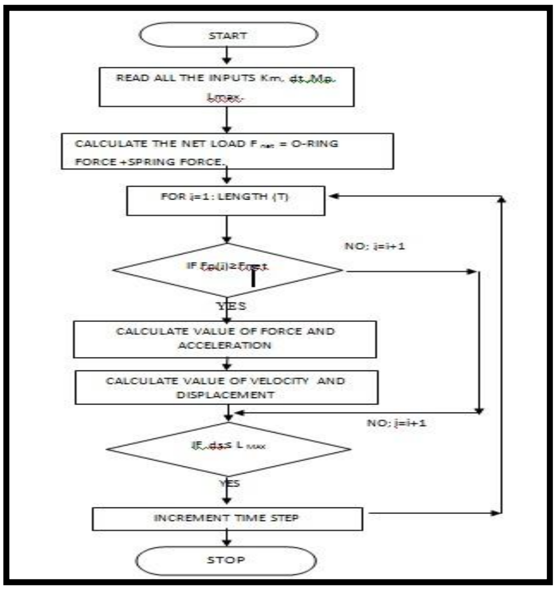
$$m_{act} = Cd.\ \rho o.A1.\sqrt{}\ ((2\gamma/(\gamma\text{-}1)).(\ P0/\ \rho o).\ (R^{\ 2/\gamma} - R^{(\gamma+1)/\gamma}))$$

for choked mass flow through orifice

$$m_{act} = Cd.A1.P0.\sqrt{}\ ((\gamma/(R.T0)).(2/(\gamma+1))^{(\gamma+1)/(\gamma\text{-}1)})$$

fornon choked mass flow through orifice

Flow chart for calculations:



Module 4:

Dynamic analysis of main poppet; the time delay for Main poppet to start travel and reach the maximum specified lift.

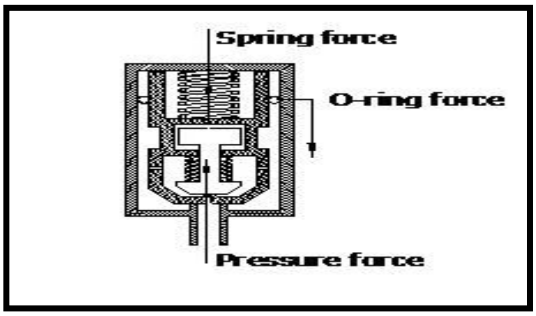


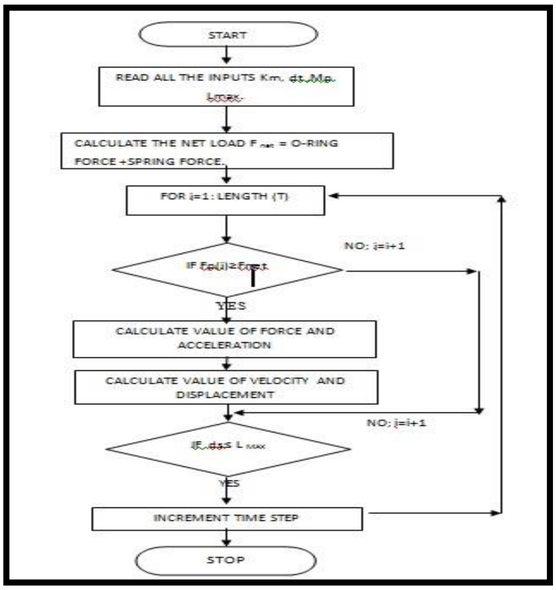
Fig 3: Schematic of main valve

Table 4 input for module 4

Serial no	Description of inputs	Values
1	Ksm- Stiffness of the main spring	8.4366 N/mm
2	Mmp-Mass of the moving parts of main poppet	0.0417 Kg
3	Lmaxmp-Maximum lift of main poppet	1 mm
4	Net O-ring force	24.525 N
5	Fsmp-assembled spring load	21.582

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 07, July-2016

Flow chart for calculations:



The difference between the pressure force and the combined force constituted by spring and O-ring would be responsible for the main poppet movement. So, for the simulation of movement of main poppet we need to find the difference between the pressure force and the combined force at the start and end of a time step and take the average of it. On dividing this force by the mass of moving parts in main poppet, we get the acceleration experienced by the main poppet in that particular time interval. After getting the value of acceleration we can obtain the velocity and there by displacement of the main poppet using the basic kinematic equations of motion. Under the effect of these changed forces again the displacement of main poppet for that time step is calculated likewise displacement for next time step is calculated and is repeated still the sum of all displacements become equal to maximum lift of the main poppet which is equal to 1 mm. Under this conditions the sum of all time steps will give the net response time for main poppet

IV RESULT AND DISCUSSION

The output of one module becomes the input to the second module. For all the modules the time span selected is 1 second (1000milliseconds) and result from each module generally describes how the output parameters is varying in this time span of 1 second . For the first module, the output is the variation of magnetic force with respect to time, which forms the input to the next module. The following figure Fig 4 shows the variation of magnetic force with respect to time.

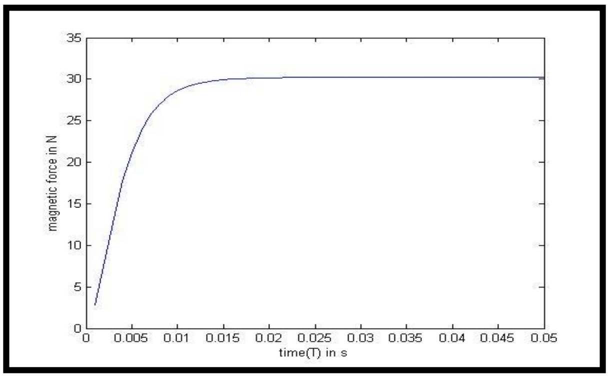


Fig 4: Magnetic force acting on pilot vs. time

From figure we can see that within the 15th ms itself the magnetic force reaches the maximum value which is 30.1 N and remains same for the entire time span. The pilot valve will start to move only when the magnetic force exceeds the spring load and pressure load. From this graph we will be interested in the point where the magnetic force is just exceeding the spring and pressure load, which tells us the time at which the pilot starts to move. As per the spring drawings the assembled load is 7.4N and the pressure load corresponding to 2.8MPa is calculated as 1.03N. The net load that the magnetic force needs to overcome is (7.4+1.03) =8.43N.

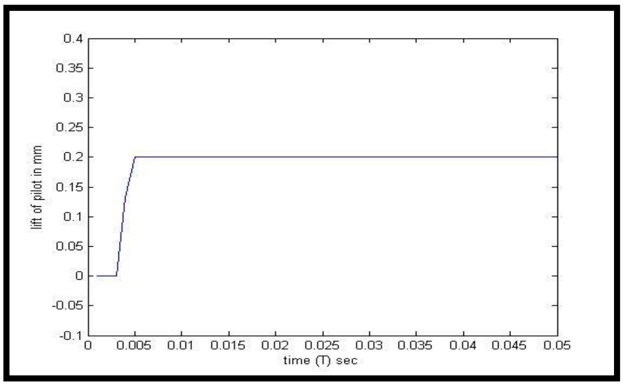


Fig 5: Lift of the pilot poppet vs. time

According to the Fig 5 the pilot starts to move from the third millisecond and reaches its maximum displacement at 5 ms and remains at that position for the remaining time span. This is because of the less mass (0.0085kg) of the pilot due to which even a very small force can produce a high acceleration

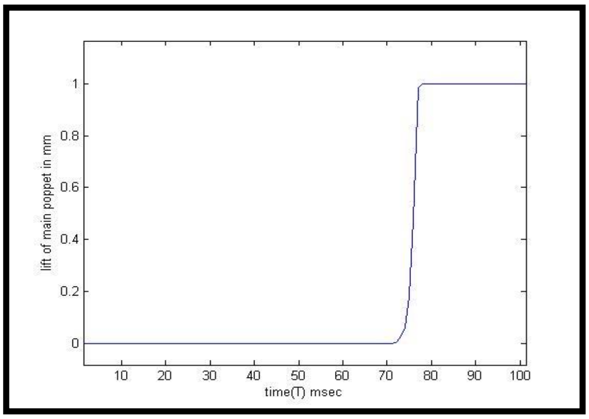


Fig 6: Lift of main poppet vs. time

From the Fig 6 we can see that the movement of the main poppet commences at 72ndms and from there it took 6 ms to reach its fully opened position. From this graphs the net pneumatic delay which is the times taken by the pressure force to built up and thereby make the valve to open, is found to be 73 ms. And the total delay which is the time takenby the main poppet to reach it’s fully opened position starting from the point at which the solenoid valve is switched on is found to be 78 ms the total delay as obtained from test results are 72 ms

Comparison of the analysis results with test results of the hardware developed

Response characteristics of the developed hardware for Load (with source pressure) are plotted in Fig 7. The no load curve will directly give the electrical delay of the valve. During loaded time the

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 07, July-2016

electrical delay of the pilot valve could not be measured since the pilot has two movements,initial movement due to magnetic and then upward lift along with the main poppet. The total response of the valve is measured from time of giving electrical command to the time to build up 90% of the maximum thrust developed. Since there was no chamber pressure measurement, the thrust developed was measured using load cell.

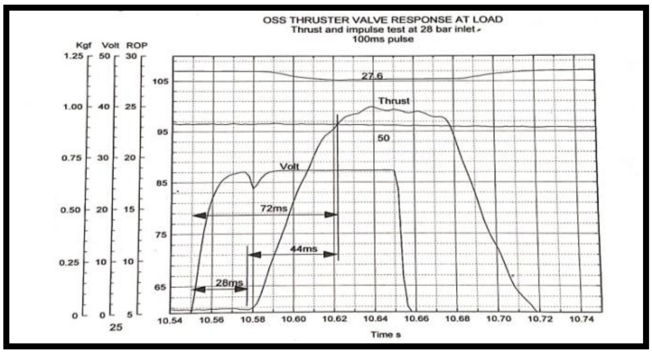


Fig 7: load Characteristics of OSS thruster valve

Parametric studies

Once the model starts to give results comparable with test results, then it can be used to study the effect of various design parameters on the desired effect. The variables selected for parametric studies are

a) air gap
b) feeding orifice diameter
c) venting orifice diameter
d) source pressure

Air gap

The air gap is varied from 0.3mm to 0.7mm by a step of 0.1mm and response time is calculated for these values of air gap keeping other parameters a constant. The results are shown on Fig. 8 below

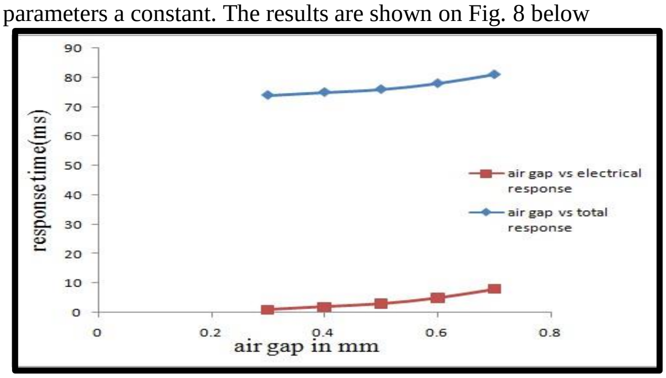


Fig 8Variation of response time with air gap

From graph we can see that as air gap increases response time also increases beyond an air gap of 0.7 mm the response time shoots up drastically because beyond that point magnetic force developed is less than spring load of pilot which it needs to overcome.

Feeding orifice diameter

The feeding orifice diameter is varied from 0.2mm to 0.6 mm by a step of 0.1mm and response time is calculated for these values keeping other parameters constant results are shown on the figure 9 below

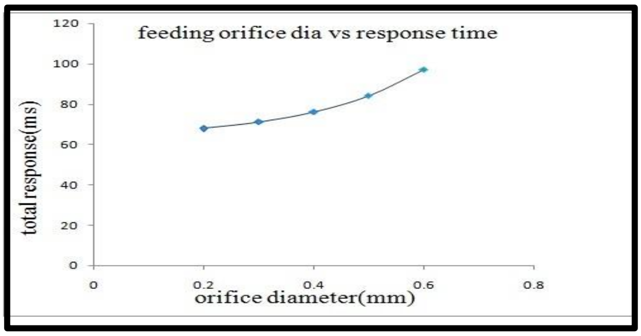


Fig 9: Variation of response time with feeding orifice diameter

From graph we can see that as feeding orifice diameter increases response time also increases. This is because as diameter increases more gas will be entering into main cavity which will delay process of lowering pressure inside main cavity and thereby increasing response time. The above graph shows that feeding orifice diameter is also a significant parameter in deciding response time.

Venting orifice diameter

The vending orifice diameter is varied from 0.5mm to 0.9mm by a step of 0.1mm and the response time is calculated for these values keeping other parameters constant. The results are shown on Fig 10 below

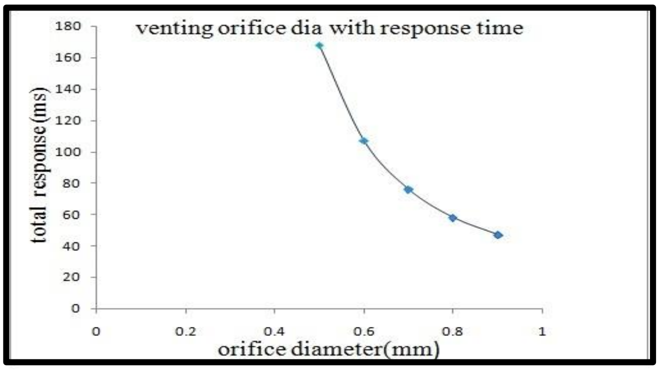


Fig 10: Variation of response time with venting orifice diameter

From graph we can see that as vending orifice diameter increases, response time decreases. This is because as venting diameter increases mass of gas leaving main poppet cavity increases which in turn leads to a faster pressure drop and thereby reducing the response time.

The source pressure is varied from 2.6MPa to 3.0MPa by a step of 0.1MPa and response time is calculated for these values keeping other parameters a constant. The results are shown on figure below;

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 07, July-2016

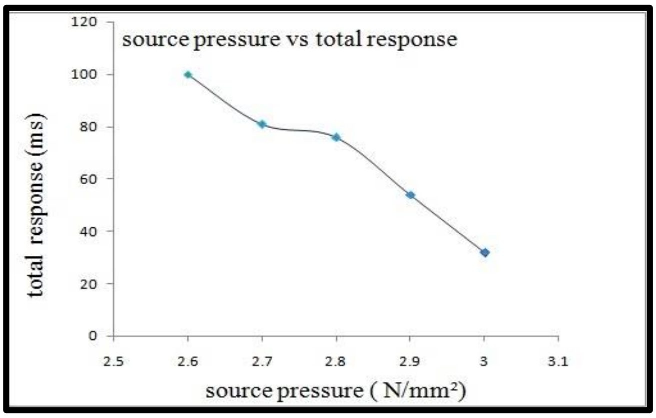


Fig 11: Variation of response time with Source pressure

Here as source pressure increases response time decreases. This is because as the source pressure increases, net upward pressure forces also increases which causes main poppet to quickly open and thereby reduce response time. This shows that source pressure is a significant parameter in deciding the response time.

V: CONCLUSION

Here in the paper I am tried to model the valve mathematically and thereby to produce a complete idea about the response time and performance of the thruster valve the model results are compared with the actual test results of the hardware developed. Validated model is used to study the effect of critical design parameters on response time and developed a program in mat lab software.

The critical parameters selected for the analysis are, Air gap, venting orifice diameter, Feeding orifice diameter, and Source pressure

Results of the study can be used to optimize the design. Optimum values suggested for minimum valve response time are;

Air gap	: 0.3mm
Venting orifice diameter	: 0.9mm
Feeding orifice diameter	: 0.2mm
Source pressure	: 2.7 to 3 MPa

With these parameters the dispersion in the value of opening response will be between 50 ms to 78 ms, which will meet the mission requirements.

REFERENCE

[1] Liu Lei, Zhang Desheng, Zhao Jiyun" Design and Research for the Water Low-pressure Large-flow Pilot-operated Solenoid Valve"Strojniškivestnik - Journal of Mechanical Engineering 60(2014)10, 665-674

[2] K. A. Venkataraman, K. Kanthavel, B. Nirmal Kumar" Investigations of Response Time Parameters of a Pneumatic 3/2 Direct Acting Solenoid Valve under Various Working Pressure Condition", ETASR - Engineering, Technology & Applied Science Research Vol. 3, No. 4, 2013, 502-505.

[3] B. W. Anderson, The analysis and design of pneumatic systems, John Wiley & sons, 1967

[4] Qianfeng Liu, Hanliang Bo, Benke Qin "Optimization of direct action solenoid valve based on Cloud PSO"Institute of Nuclear and New Energy Technology, Annals of Nuclear Energy 53 (2013) 299–308

[5] Qianfeng Liu, Hanliang Bo, Benke Qin "Design and analysis of direct action solenoid valve based on computational intelligence"Nuclear Engineering and Design 240 (2010) 2890–2896

[6] Steven T "Karris Numerical Analysis Using MATLAB and Excel" Third Edition, Orchard Publications, 2007.