STUDY ON EXTRA-HIGH SPEED DIGITAL VALVE

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ABSTRACT

Extra-high Speed Digital Valve has been studied for a decade by the authors. This paper presents the study results with two aspects such as in hydraulics and electronics.

Digital valve must become next generation for hydraulic technology. In this paper, one application area in fuel injection requires extra-high speed as high as 2000 Hz. Providing the ability of fast response and high traction force, and a simple construction, a new concept for this valve is presented herewith.

Some simulation results as well as experimental results show that the new extra-speed valve has been developing.

NOMENCLATURE

t = time (s)
ì$_0$ = permeability of air (H/m)
ì$_s$ = permeability of air (H/m)
U = voltage (V)
I = circuit current (A)
R = circuit resistance (Ù)
N = number of coil turn
x = plunger displacement(m)
Ö = magnetic flux (Wb)
B = magnetic flux density (T)
H = magnetic field (A/m)
M = mass of moving parts (kg)
F_{mag} = magnetic force (N)
F_T = spring setting force (N)
Fp = reaction force caused by the flowing oil

1. INTRODUCTION

Since 1980's, of high-frequency, anti-polluted ability and low price of digital valve is being required by electronic-hydraulic control systems. Fast-acting electromagnetic actuators are continually finding new applications in these areas such as the automotive industry. To utilize these actuators effectively in critical situations such as fuel injectors, ABS system, etc., accurate mathematical models of the devices must be available to aid in the valve designation and production.

A.H.Seilly, British Lucas corporation, firstly started their research in the high-speed digital valve, and two kinds of solenoid have been researched: Helenoid[1] and Colenoid[2]. Between these two valves, there was special construction in solenoid to balance increased electromagnetic force with decreased acceleration of traditional solenoid. But their structures were very complex and hard to be manufactured. So their application was limited. Meanwhile, G.Mansfeld, J.Tersteegen and K.Engelsdaf, P.Dnnken began to do research in this area. The valve they designed had 2ms response time but complex structure [3]. And from then on, experts in Ford Motor developed a kind of fast response multi-pole solenoids whose response time is 2ms[4]. In 1984, BKM corporation developed a fast response digital valve applied in median-pressure common real fuel injection system for diesel engines, which open time was 3ms, close time was 2ms under working pressure 10Mpa[5]. In Japan, Diesel KiKi corporation developed a dish like “DISOLE” solenoid, it had large force and 0.74ms response time, but large structure. In China, Beijing Institute of Technology, Tsinghua University, Tianjin University, Gansu University of Technology, Zhejiang University, Shanghai No.1 Hydraulic Component Factory, Shanghai Jiaotong University, etc., have designed and studied some kinds of digital valve [6,7,8,9,10,11].

2. THE WORKING MECHANISM OF THE HIGH- SPEED DIGITAL VALVE

Accurate mathematical models of the devices must be available to aid in the design process such as fuel injection application. Optimization and control strategy used the model for greatly reducing the number of prototypes required while simultaneously improving the performance of the final product. By means of the 3M(Module Modeling Method, the authors presented ten years ago[9,10]), a model for fast-acting, electromagnetic actuators has been developed which accounts for magnetic saturation, flux leakage, eddy currents, fluid damping with inertia effects, and the dynamic coupling of all actuator state variables. Moreover, this has been attained while preserving the simplicity of a lumped-parameter approach and with a minimum of empiricism. And it is verified a effectual modeling method in analysis and design coupling systems.

The high-speed digital valve is an electromagnetic actuator, consisted of four distinct and sometimes strongly coupled subsystems, namely electrical, magnetic, mechanical and fluid. Fig 1 schematically illustrates the basic interrelationships among these four partially represented by the interconnecting lines; for example, the rate of change of flux linkage, $d\,l / dt$, is not only a function of magnetic subsystem parameters but also is a function of the armature position, *x*, the armature velocity, $\dot{x}$, and the time derivative of the coil current, *di/dt.* The armature acceleration, however, is determined by the magnetic and fluid forces, which are, in turn, functions of the armature position, armature velocity, electric current, and other variables. Clearly, the overall system behavior is not solely defined by simple expressions describing the internal behavior of individual, isolated subsystems. In the following sections, the governing equations for each of the subsystems are developed and the coupling between these subsystems is shown explicitly.

3. DESIGN RULE AND SIMULATION

Analyzing the four subsystems respectively, we got the interrelationships between them as shown in equation (3-1).

In order to achieve fast response, it is necessary to find the limitations of performance, and to do this, numerical analysis is required.

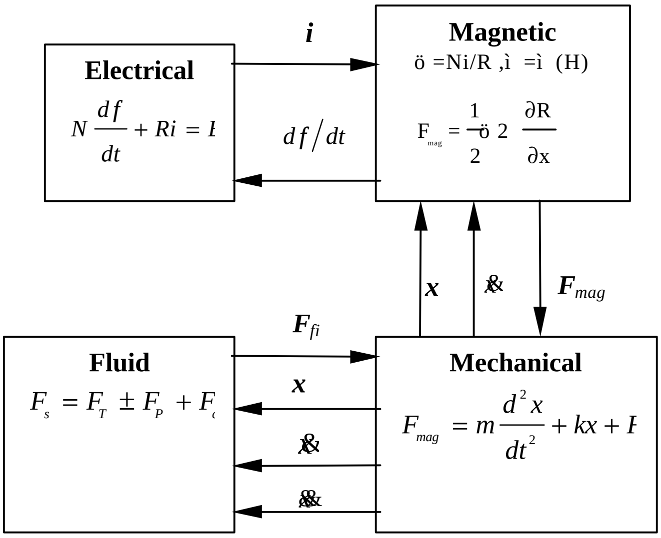

Fig.1 Schematic of electrical, magnetic, mechanical and fluid subsystems showing basic subsystem interrelationships

$$\begin{cases} \dfrac{di}{dt}=\dfrac{U-R\cdot i-(dL(i,g(i,x))/dx)v\cdot i}{L(i,g(i,x))} \\ F_m=F_z=\iint_S p_z\cdot ds \\ \ddot{x}=\dfrac{1}{m}(F_m-F_T-F_P-F_c) \end{cases} \qquad (3\text{-}1)$$

Since the key to a fast response in a solenoid is its ability to absorb input energy at high rate during the activation period, we should find out what is the optimum schedule of energy flow into the solenoid coil, which will assure the required speed of response with minimal energy input. The usual schedule of solenoid activation involves application of a voltage pulse of a constant magnitude for the duration of the activation period. During this time the current approaches its maximum value. The flux density and the traction force increase and reach their minimum values ant the end of the armature travel. Then, the current is reduced to a minimum value necessary to keep the armature in place during the holding period. At the beginning of the armature travel, the traction force is small. Because of that, the movement of the armature is initially slow, and most of the travel takes place at the very end of the activation period.

The travel time can be reduce if the maximum traction force, which is determined by the saturation flux density and the face area of the solenoid, is achieved early in the armature travel, so that the armature is driven with maximum acceleration during most of the travel time. This requires not only very fast current rise, but also very high value of peek current, since the saturation flux density must be achieved while the air gap is still large. However, as the armature travel reduces the air gap and the reluctance of the magnetic circuit decreases, the current can be gradually reduced, while the reaction force remains constant. Figure 2 shows a graph of such an optimized current pulse, as well as the voltage and traction force graph during the solenoid activation period. The resistance of the coil is very low, relative to the applied voltage, at the current is not allowed to rise to its steady stage value, determined by the Ohm's law. The initial portion of the current rise curve, where the current rise rate is the fastest, is utilized. The unused potion of the current rise curve, for $t>t_1$, is shown as a lantom in the graph. From time t_0 to t_1, the voltage remains constant, and both the current and the traction force rise rapidly. At time t_1, the flux density approaches the saturation level, and the traction force achieves its maximum value F_1 the value of current I_1. At this point, further increase in the magnitude of the current becomes useless, and step change in the applied voltage from the initial value v_0 to v_1 terminates the rise of the current. Form time t1 to t_2 the voltage is gradually reduce form v_1

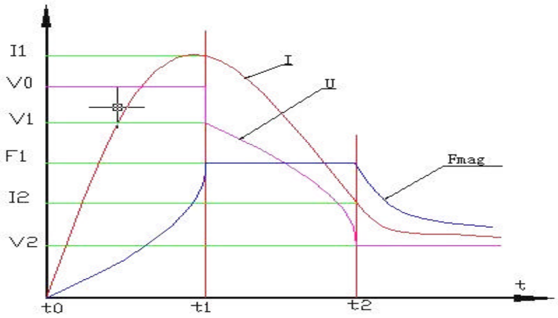

Fig.2 The Driving Scheme

to v_1. the current decreases form I_1 ant *t1* to I_2 at t_2. The decline in current is tailored so that it is compensated for by a concurrent reduction by the air gap, and the traction force remains its maximum level F_1. At time t_2 the stage drops to v_2 and current decreases to a low level I_3 sufficient to hold the armature in place during the holding period. The power consumption reaches its maximum at time t_1, when both the current and the voltage reach at their peak values, and then rapidly declines during the remaining portion of the activation period.

Furthermore, according to the analysis of Fig.2, control method, power consumption and temperature rise must be calculated since the amount of input energy depends on the limitations on temperature rise. Stress analysis is also necessary. This enables the calculation of minimum dimensions of an armature of minimum mass which would endure the repeated stress under which a moving armature operates. During development of the valve, these analyses were executed. Firstly, we founded the method of computerized simulation do dynamic behavior, including magnetic circuit analysis, then the models for each of these four subsystems. Fig.3 show the construction of program.

4. CONCLUSIONS

By introducing the 3M method, we have developed the mathematical method for the high-speed digital valve which makes it possible to perform design calculations in a short computation time with the help of a limited-capability computer. It has been confirmed that agreement that agreement is good between the simulation results produced by the 3M method and the result of the experiment. We repeated manufacturing and test trials to develop the high-speed digital valves, and performed simulation based on the 3M model for efficient development. As a result, the main points derived from our research are summarized below:

a) Applied Voltage and Current—The applied voltage must be high and should be around 24v. The maximum current needs not to be higher than 50A.

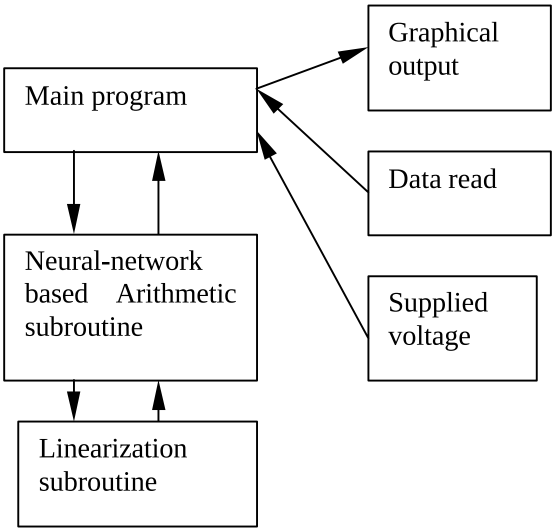

Fig.3 Construction of Calculating and Simulating Program

b) Magnetic Materials—To suppress the generation of eddy currents, a material with low conductivity is advantageous as expected. In addition, a material with high saturation magnetic flux density is favorable.

c) Magnetic Path Length—Shorter is better, but the magnetic path length has a smaller effect than other factors have.

d) Stoke and Flow Force—The stroke should be small. Extending the stroke should be averted in order to reduce the flow force.

e) Coil Specification—By connecting coils in parallel high-speed operation can be achieved while ensuring the holding force after switching.

f) Armature Mass—In order to achieve high acceleration of the armature, the armature mass should be small.

g) Sealed Quality—The digital valve is working under the high-pressure situation, and it should be sealed well.

h) Heat-emitted Performance—Because high energy injected through the coil and high press by the flowing oil, it maybe generate lots of thermal energy, which may lead to burn out the oil and distorting the valve. So the heat-emitted design should also be designed.

The key to a fast response in a solenoid is its ability to absorb input energy at high rate during the activation period. Optimizing the schedule of the power input into the solenoid coils leads to further improvement in solenoid performance. The Modularized Modeling Method derived in this paper permit the design of both a fast response solenoid and of an efficient schedule of electrical power delivery to the solenoid.

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