FLUCOME 2007 Tallahassee, Florida

# THE MINIATURIZATION OF FLOW CONTROL

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## ABSTRACT

As technologies and products are developed and refined there is a general tendency toward miniaturization. Fluid flow control is certainly no exception and a new MEMS control valve technology has been developed that is applicable to low and mid-range fluid control. Similar to the development of electrical circuitry from vacuum tubes and relays to the integrated chip, control valves have now with this technology transitioned from solenoids to MEMS with micron sized features to reduce size and weight and to further enable control valve system integration.

The MEMS micro valve is able to control fluid flow by using a pressure balanced plate-type valve where the plate position is controlled by the thermal expansion and contraction of ribs that conduct electrical power. Direct acting and pilot/spool configurations can be used depending on required flow rates. The MEMS valve has been shown to control fluid flow at pressures in excess of 2,000 psi and with flow rates comparable to many solenoid valves. Integration with sensors and electronics has also been shown to miniaturize the control valve system in ways that are unavailable in solenoid control valves.

While MEMS valve performance is comparable to common solenoid valves in terms of fluid flow, the valve's size, weight, and system integration characteristics provide an effective way to miniaturize many of the control valves, and related components, in today's fluidic circuits.


**Keywords: Flucome 2007, MEMS, Control Valve, Micro Valve, Plate Valve, Flow Control, Miniaturization**

## INTRODUCTION

As technology is developed there is a general tendency towards making products smaller. However, there are usually constraints that tend to limit size reduction within a certain technology. Microelectromechanical systems (MEMS) is a technology that has been developed to eliminate many of the design constraints found in previous technologies. Several MEMS products have been developed that are now used in every-day applications: optical switches, gyroscopes, accelerometers, pressure and temperature transducers, inkjet printers, etc.[1] [2] A few MEMS products for the fluid control industry have been developed for limited low pressure and low flow applications and are not yet readily available. However, due to recent developments in MEMS technology and creative design a new MEMS control valve has been developed for use in common applications of low to mid-range pressure and flow.

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Solenoid control valves are commonly used in many applications in the fluid control industry and have several desirable features: on/off or proportional response, fast response time, scalability, and low cost. As an example, Figure 1 shows a solenoid valve that is used to control the crankcase pressure inside an automotive air conditioning compressor. This valve controls flow of up to 45 L/min and pressure differentials up to 4.1 MPa in an R134a refrigeration system. The solenoid valve overall size is 93 mm T x 28 mm DIA and it has 2 main flow ports.

**Figure 1: A solenoid control valve**

Solenoid valve technology also has constraints that limit how this type of valve can be used: a mature technology that makes cost reduction difficult, EMF noise due to induction, and the significant size and weight of the coil. Cost reductions have been elusive due to the lack of new breakthroughs in solenoid design as well as an increase of copper prices over 500% in the past 8 years.[3] EMF noise is inherent in a coil and can only be masked through extra effort. The size and weight of a coil are directly related to the amount of force needed to control the fluid flow. Through the use of MEMS technology these constraints can be eliminated or reduced to enable a fluid control valve to be used in places and in ways that can significantly enhance the control of a fluidic system.

## TECHNOLOGY OVERVIEW

### A MEMS Plate Valve

The MEMS control valve technology is based on a three layer plate valve configuration which consists of three key design features: a moving center layer, the control of the moving center layer, and leakage mitigation. The moving center layer is a portion of the middle of the valve that moves relative to ports in one (or both) of the outer layers. The motion of the center layer opens and closes passages between two or more ports located in the outer layers. Figure 2 shows a typical section view of a three layer plate valve with three ports. The left port is open to the center port and the right port is closed to both the left and center ports. As the orange region of the middle layer simultaneously moves to the right the left port closes to both the center and right ports while the right port simultaneously opens, as shown in Figure 3.

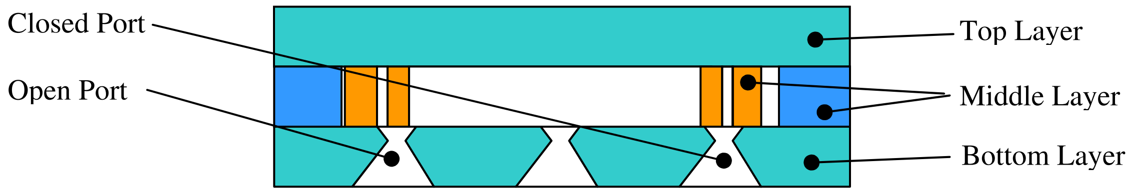


**Figure 2: A three layer plate valve with the left port open and the right port closed.**

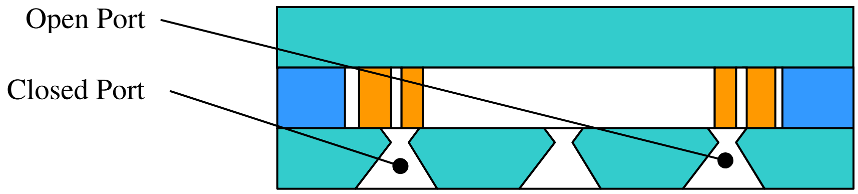


**Figure 3: A three layer plate valve with the right port open and the left port closed.**

Positional control of the middle layer is critical in the ability of the valve to provide on/off or proportional control. As fluid flows through the valve at increasing velocities there are inherent forces that can adversely affect the position of the center layer that are generally proportional with increasing flow rates. These forces must be properly balanced in all conditions to ensure movement is properly controlled.

Leak mitigation in a plate valve is accomplished by controlling the clearance between the cover layers and the moving portion of the center layer. If this clearance is too large the flow adversely affects the performance of the valve. Conversely, if this clearance is too small the middle layer can't move due to interference. Because of the tight process control in MEMS fabrication processes this clearance is significantly minimized to reduce leakage without restraining the middle layer.

**The Direct Acting Valve**

In applications where fluid flow rates are low positional control of the middle layer is accomplished by means of thermal expansion. Figure 4 shows a direct acting valve that has a set of ribs, an arm, and six ports. The ribs consist of a set of four pair of long thin columns at a slight angle positioned between an isolated pad at the bottom and the fixed frame. As electrical current passes through the rib structure heat is proportionally generated by the resistivity of the doped silicon. Due to the elevated temperature the ribs expand more than the surrounding frame and translate the motion to the arm through a strut. The arm is an 'I' shaped feature in the center of the valve. As the rib strut moves to the right due to rib expansion the top of the arm translates to the right and the bottom of the arm translates to the left in a slight clockwise rotation about the pivot strut. Through this arrangement the proportional rib expansion is amplified approximately 100 times at the ports.

The six ports are configured to be two sets of three ports; one set at the top and one set at the bottom, that operate as previously described. When there is no power supplied to the ribs the upper section of the middle layer is positioned over the ports as shown in Figure 2 and the lower section is positioned as shown in Figure 3. When full power is applied the configurations are reversed so that the upper section is positioned as shown in Figure 3 and the lower section is positioned as shown in Figure 2.

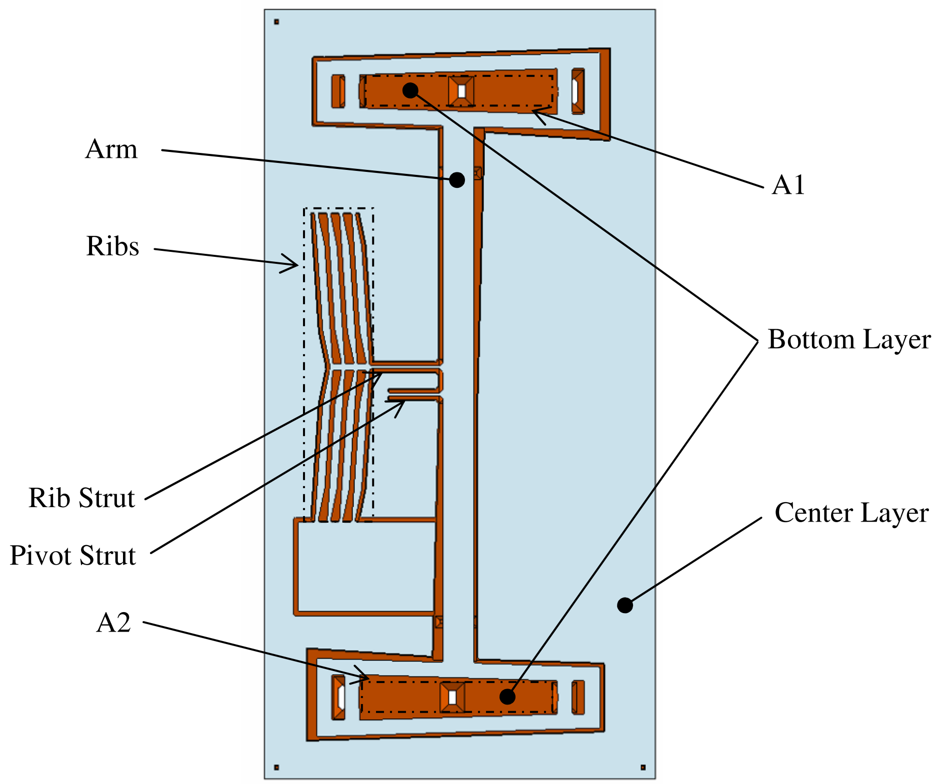


**Figure 4: A 6 port direct acting MEMS valve shown in the power off configuration and without the top layer.**

When compared to a solenoid control valve of similar flow capabilities the MEMS valve is able to significantly minimize the effects of the constraints of a solenoid control valve: cost is comparable to a solenoid valve due to the batch processing of MEMS devices and future cost savings are conceivable as the technology matures; EMF noise is eliminated by using ribs; and the overall size is significantly reduced to 12 mm H x 6.5 mm W x 2 mm T.

**The Spool Valve**

As fluid flow rates increase the reaction forces applied to the internal parts of a valve also increase. A pilot/spool configuration can be used in applications where forces due to fluid flow can overpower the relatively small forces generated by a set of thermally expanding ribs. In this arrangement the direct acting valve is used as a pilot valve to drive a larger MEMS spool valve like the one shown in Figure 5.

The MEMS spool valve, similar to the direct acting valve, is a MEMS plate valve and has the same key design features. However, because the flow rates through the spool valve are significantly higher than the direct acting valve the method of controlling the position of the spool, relative to the ports, is accomplished through hydraulic leverage. The pressure and area differentials between A1 and A2 create a resultant force that causes the spool to move in the same direction. When the resultant force is in the upwards direction the main port opens and flow can pass through the valve, as shown in Figure 5. When the resultant force is downwards the spool is closed and flow is shut off. The pressures in A1 and A2 are controlled by the respective areas of the direct acting valve.

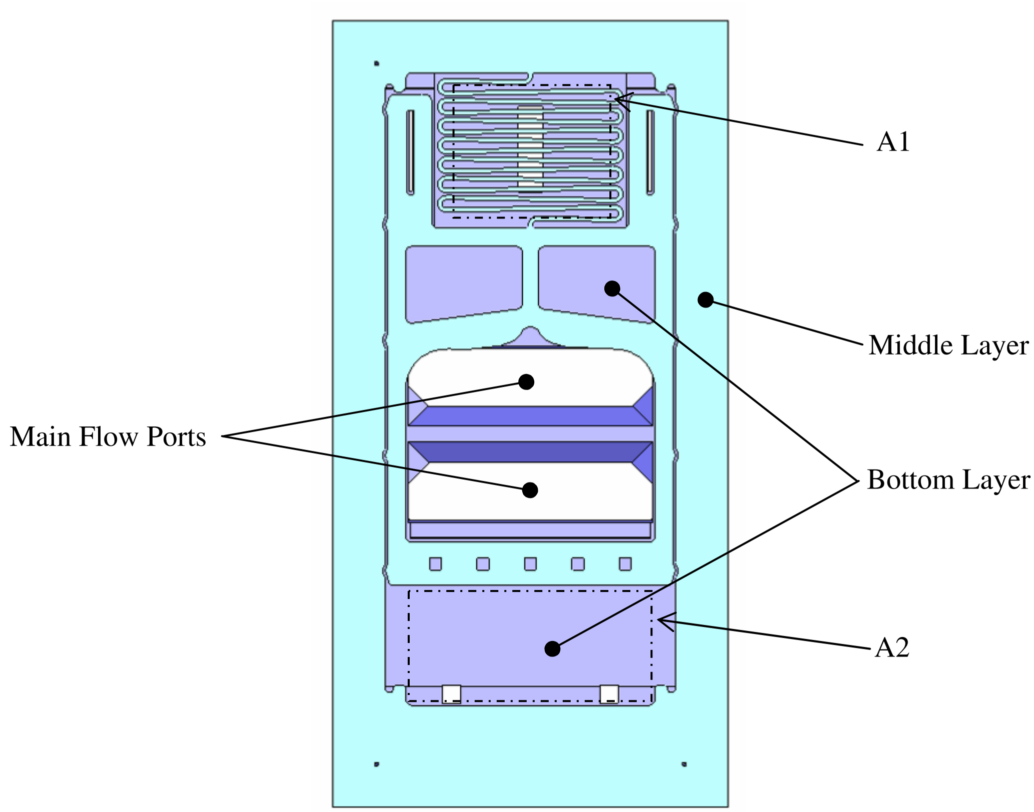


**Figure 5: A two port MEMS spool valve shown in the open configuration without a top layer.**

Similar to the MEMS direct acting valve, the MEMS pilot/spool valve resolves the constraints of a solenoid valve of similar performance. The MEMS pilot and spool valve combination is much smaller than a solenoid control valve and is twice the size as the direct acting valve.

### System Integration

The MEMS control valve can be integrated into a fluidic system in various configurations ranging from a direct replacement for an open loop control solenoid valve to a redesigned localized closed loop control system. In any case, the control valve is soldered to a manifold to effectively bridge the gap between ports on the MEMS scale and system ports. If a closed loop system is employed complimentary technologies of MEMS transducers and integrated chips (ICs) can also be attached to the manifold for localized closed loop control to significantly reduce the system package size, cost, and response time.

### Basic Manufacturing Process

The MEMS control valve is built in four general steps: the MEMS valve, the manifold, the electronics, and the final assembly. First, the MEMS valve is manufactured using typical MEMS processes of wet etch, dry etch, fusion bonding, metal deposition, and dicing. Three silicon wafers are individually processed to create each of the three layers that make up the valve. Each wafer has multiple instances of the MEMS valve design replicated over the entire wafer. The two outer layers are fabricated using several anisotropic KOH etches to create the ports and various relief features. The outer layers are then covered with an oxide to provide electrical isolation of the middle layer and to facilitate fusion bonding. The middle layer is fabricated using a DRIE process. Some spools that have been detached from the rest of the middle layer of a spool valve are shown in Figure 6. Once the three layers have been individually processed they are aligned and fusion bonded together. Next, a metal deposition process is used to create the surface used to solder the valve to a manifold. Finally, the individual valves are diced from the wafer. A manifold is build by using standard CNC machining, brazing, and metal plating processes. CNC machining creates passages and holes in multiple steel layers that are then brazed and plated. The electronics, if used, are also built using traditional processes. The final assembly is built by soldering the MEMS valve to the manifold and by wire-bonding the needed electrical connections.

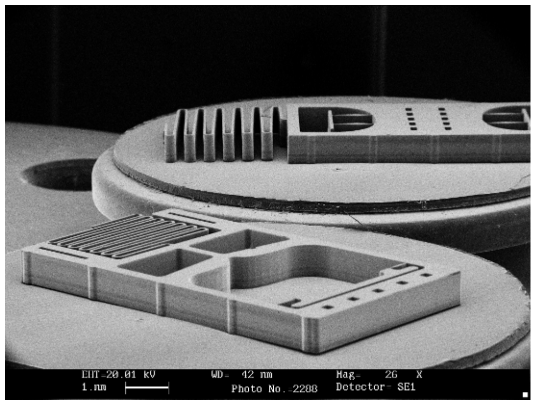

**Figure 6: Spool and spring portions from two different MEMS spool valves.**

## AUTOMOTIVE A/C COMPRESSOR CONTROL

A system that benefits significantly from the advantages of MEMS control valve technology is an automotive air conditioning (a/c) system. In most of today's automotive a/c systems a variable displacement compressor is used to drive the refrigeration cycle. The compressor's output is predominantly controlled by adjusting the pressure of the refrigerant in a crankcase chamber, $P_c$. As $P_c$ is increased the output of the compressor is decreased and suction pressure, $P_s$, increases to provide reduced cooling capacity. As $P_c$ is reduced the compressor output is increased and $P_s$ reduces to provide increased cooling capacity. $P_c$ is established by controlling an opening between discharge pressure, $P_d$, and $P_c$. This opening is typically controlled by a solenoid valve, an example is shown in Figure 1. A fixed orifice between $P_c$ and $P_s$, is used to reduce $P_c$. Generally, an automotive a/c control valve is required to be able to control $P_s$ in a smooth, linear response to a command signal between minimum and full compressor output. The command signal used to drive the control valve is typically a pulse width modulation (PWM) signal at 400 Hz where the duty cycle is adjusted from 0% to 100% to deliver an average current to the control valve.

A typical solenoid control valve controls $P_s$ as shown in Figure 7. In this particular system, $P_s$ is controlled in a relatively linear response by the solenoid control valve when command current is between 0.2 A and 0.7A. Maximum compressor output is shown at the beginning and end of the chart where $P_c$ is lower than $P_s$. Minimum compressor output is shown in the center of the chart where the differential between $P_d$ and $P_s$ is at the minimum. Although the control of Ps is relatively good, there are some points where $P_s$ control is not linear and is emphasized by large jumps in $P_d$. Also, the full range of the electronic signal does not affect $P_s$.

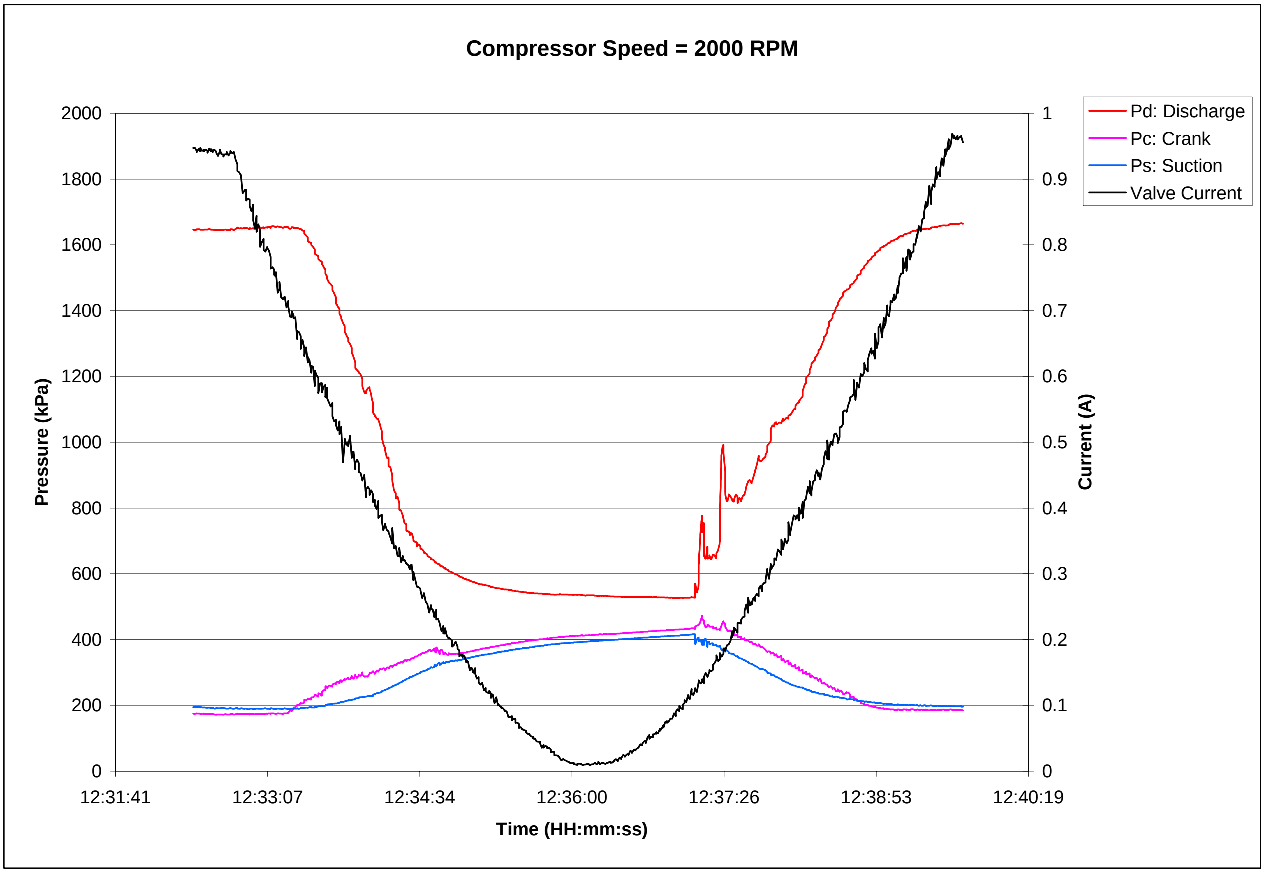


**Figure 7: Solenoid Valve $P_s$ Control**

A MEMS control valve configured as a localized closed loop control system can be used to control $P_s$ in place of the solenoid control valve. Figure 8 shows similar maximum and minimum output responses and an improved linear response in $P_s$ over a larger range than the solenoid valve. Also, $P_s$ is controlled over the full range of command. There is, however, a relatively large change in $P_s$ as the compressor output begins to increase from minimum output but subsequent pressure jumps seen in Figure 7 are not seen in Figure 8. The large variation in electrical current shows the closed loop feedback keeps Ps on target by actively adjusting the power level supplied to the MEMS valve. The large range in variation can be reduced by implementing a PID control scheme.

In addition to improved $P_s$ control, the MEMS valve offers several advantages over the solenoid control valve in design flexibility. By eliminating EMF noise and reducing package size the location of the control valve on the compressor, and related transducers elsewhere in the system, can be redesigned for increased system efficiency. For example, a much smaller rear head could allow the compressor to be packaged more effectively in the engine compartment; pressure and temperature transducers could be relocated to the MEMS valve manifold as MEMS transducers to eliminate the associated cost of assembly and wiring; and significant weight savings can be realized for improved vehicle efficiency.

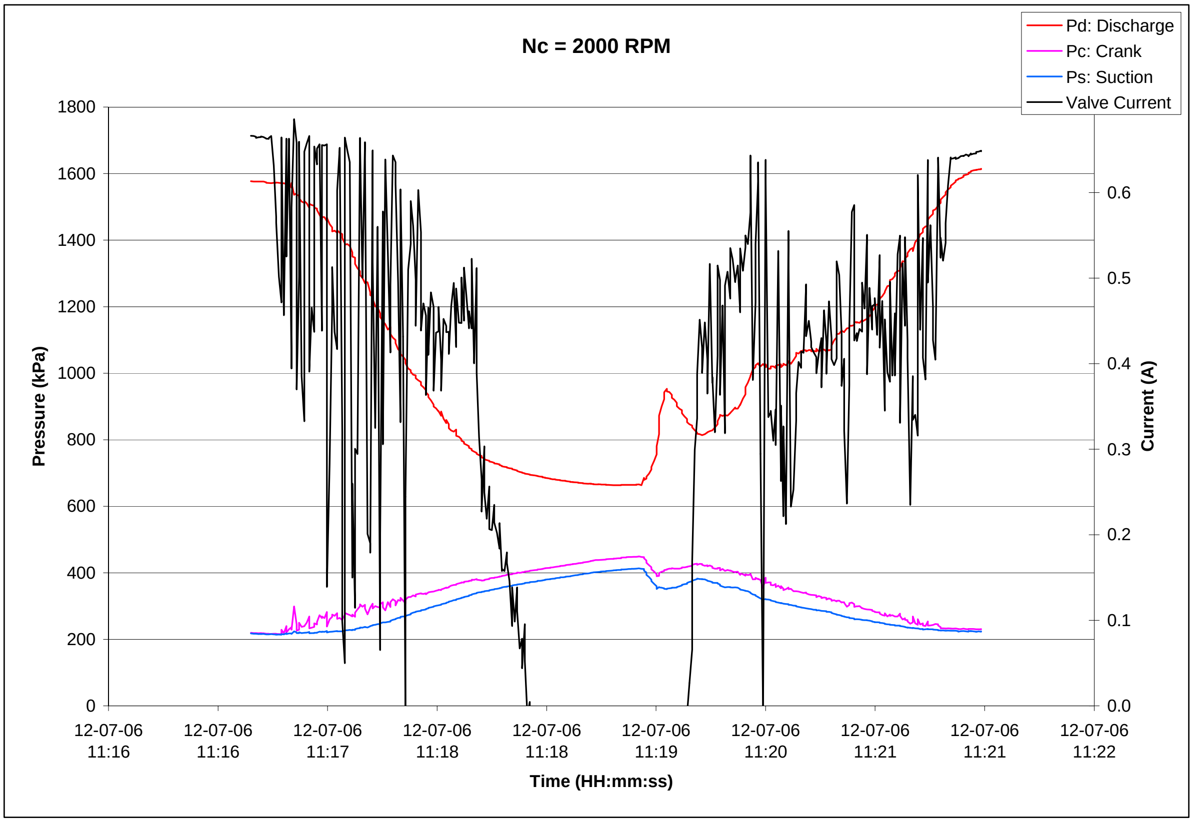


**Figure 8: MEMS Valve $P_s$ Control**

## CONCLUSIONS

A new MEMS control valve has been developed to resolve the key constraints of current solenoid valves while maintaining or improving system performance. This valve is comparable in cost to current solenoid valves yet contains promise for future cost reduction as MEMS control valve technology matures. EMF noise created by the coil in a solenoid valve is completely eliminated in the MEMS valve by using a resistive load in the ribs to cause actuation. Overall size is reduced by more than 75% to allow greater integration with transducers and electronic control circuitry and to provide more freedom in system design and control.

The MEMS control valve has shown to be capable of meeting the requirements of various applications ranging from automotive a/c and transmission control to metering valves in equipment control. With continued improvements in closed loop electronic control and further development in open loop control the MEMS control valve will become an effective way to minimize the fluid control systems.

## REFERENCES


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