DEVELOPMENT OF ELECTRO-PNEUMATIC VALVE FOR COLD AIR FLOW CONTROL

Yasukazu SATO*, Shengnian CAI** and Nobuyoshi HASHIMOTO**

* Department of Mechanical Engineering, Graduate School of Engineering
Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan
(E-mail:sato@post.me.ynu.ac.jp)
** Shinwa Controls Co. Ltd.
2-8-4 Gorikida, Asou-ku, Kawasaki, Kanagawa 215-0025, Japan

ABSTRACT

Dry-cutting/grinding system utilizing compressed cold air is environment-friendly machining since it uses no cutting/grinding oil and the cutting chips are easy to recycle. In this system, the control valve dealing with the cold air of -10–30°C has to satisfy both the insulation from heat sources around and the linkage with an external valve-actuator. The former is avoidance from heat transfer and the latter is connection with heat conductor. For the requirement of two contrary functions, we have developed an electro-pneumatic valve that equips both the vacuum insulation layer inside and the latch-mechanism using the magnetic force of a permanent magnet. The thermal transmittance of the developed valve, which is the index of the heat conduction into the cold air, indicates about one thirtieth of the conventional value.

KEY WORDS

Pneumatic Valve, Actuator Design, Thermal Insulation, Cold Airflow

INTRODUCTION

Dry-cutting/grinding system utilizes compressed cold air of -10–30°C instead of the conventional oil-based or water-based coolant. Since it needs no disposal of wasted coolant, extends tool life and makes it easy to recycle the cutting chips, it has lately attracted attention as environment-friendly machining [1][2]. Figure 1 shows main components of the typical system. The airflow from the chiller to the cutting point needs to be insulated from any heat sources and be kept cold for minimizing the capacity and power consumption of the chiller. In the conventional system, the thick and heavy insulating material wholly wraps the airflow line, whereas it lacks flexibility and behaves as an obstruction of high-speed movement of the machining head. Though the lightweight flexible-pipe with the vacuum isolation layer has lately developed, the control valve suitable for cold airflow has not appeared in the actual system yet. The valve has to satisfy both the insulation from heat sources around for prevention of the air temperature rise and the linkage with an external valve-actuator. The former is avoidance from heat transfer and the latter is connection with heat conductor. For the requirement of two contrary functions, we have developed an electro-pneumatic

Figure 1 Dry-cutting/grinding system configuration
(Other configuration: cold air flows through the inside of a cutting tool via a spindle)
valve that equips both the vacuum insulation layer inside and the latch-mechanism using the magnetic force of a permanent magnet, and applied the magnetic field and heat transfer analyses to the design of the electromagnetic part and the insulation layer. This paper describes a design strategy of the electromagnetic device for cold airflow control and the result of the performance test.

**VALVE FOR COLD AIRFLOW CONTROL**

Table 1 shows the design specification of the valve, and Figure 2 shows the valve structure with the vacuum insulation layer and the permanent magnet for the latch-mechanism. The detail dimensions are left out since the valve elements used in this valve are the same as in the conventional. The insulation layer consists of the coaxial sleeves of nonmagnetic stainless steel, and the chamber between them is sealed up after forming a vacuum. The latch-mechanism with some pieces of \(\text{Nd}_{2}\text{Fe}_{14}\text{B}\) permanent magnet (denoted as "PM" in the following) is effective to reduce the generation of heat at the coil because the actuator needs no electric power in steady state and utilizes the magnetic force of PM while the stator holds the plunger. The instantaneous coil current works as motion trigger. The positive current assists the magnetic force of PM to overcome the spring load; the negative current reduces the force for returning. The yoke-A and yoke-B connect with the inner sleeve to close the magnetic circuit at the end and middle of the sleeve. In order to prevent the heat flux from flowing into the cold air, the yoke thickness at the connection points should be designed to be as thin as possible for having high thermal resistance unless the magnetic flux density is saturated there.

**BASIC ACTUATOR DESIGN**

**Electromechanical Design**

The magnetic circuit was roughly designed using the classical method taking the magnetic saturation in \(B-H\) characteristics into consideration [3]. Figure 3 shows the actuator part of the valve, which is simplified for the classical method. From the electric equation, the transient current flowing through the coil is given by;

\[
E = RI + N \frac{d\psi}{dt},
\]

where \(E, I, R, N\) and \(\psi\) are the input voltage, the current, the coil resistance, the coil turn number and the magnetic flux, respectively. The relation between the overall magnetic motive force \(NI\) generated by the coil and the magnetic field intensity \(H\) over the path length \(l\) is given by;

\[
NI = \sum_{i=4}^{n} H_i l_i + H_{\text{gap}} l_{\text{gap}} + H_{\text{rad.gap}} l_{\text{rad.gap}} - H_{\text{pm}} l_{\text{pm}},
\]

where the subscripts denote the material and the loci. The first three terms in the right hand side of eq. (2) have the relation;

\[
\psi = BA = \mu HA,
\]

where \(A, B\) and \(\mu\) are the cross sectional area of the magnetic path, the magnetic flux density and the permeability, respectively. \(\mu\) in the steel part changes according to the nonlinear \(B-H\) characteristics, and \(\mu\) in the air gap is constant and is \(\mu = \mu_0 = 4\pi \times 10^{-7} (\text{Wb/Atm})\). The magnetic property of the permanent magnet part is expressed by the demagnetization curve, which is approximated by;

\[
B_{\text{pm}} = \mu(H_{\text{pm}} - H_c) = \mu R H_{\text{pm}} + B_c,
\]

where \(B_{\text{pm}}\) and \(H_{\text{pm}}\) are the magnetic flux density and field intensity at the driving point on the demagnetization curve, \(H_c\) is the coercivity, \(B_c\) is the

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Table 1 Valve specifications (Design values)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rates</td>
<td>11 ([\text{m}^3/\text{h}])</td>
</tr>
<tr>
<td>Air temperature</td>
<td>-30 ([\text{C}])</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.69 ([\text{MPa}])</td>
</tr>
<tr>
<td>Solenoid power consumption</td>
<td>10.2 ([\text{W}])</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>Attract: 24 ([\text{V}])</td>
</tr>
<tr>
<td></td>
<td>Release: -10([\text{V}])</td>
</tr>
<tr>
<td>Valves switching</td>
<td>within 20 ([\text{ms}])</td>
</tr>
</tbody>
</table>
residual flux density and $\mu_r$ is the recoil permeability. The electromagnetic force attracting the plunger toward the stator is given by;

$$F_{\text{mag}} = -\frac{B_{\text{gap}}^2 A_{\text{gap}}}{2\mu_0},$$  \hspace{1cm} (5)

where the minus sign indicates that the force tends to decrease the air gap. The motion of the plunger is expressed by;

$$m\ddot{x} + b\dot{x} + k(x - x_0) = F_{\text{mag}},$$ \hspace{1cm} (6)

where $m$, $b$, $k$, $x$, and $x_0$ are the mass of the plunger, the viscous friction coefficient, the spring constant, the plunger displacement and the initial compression of the spring, respectively. The transient and the static characteristics are solved from the equations (1)–(6). Figure 4 shows the block diagram for the simplified magnetic circuit model and Figure 5 shows the simulated example of the latch-mechanism using the software MATLAB/SIMULINK. This model does not include the influence of eddy current, however, it is enough for the basic design since this valve does not require such fast switching speed that the eddy current influences on its switching. The simulated static characteristics are shown in later part together with the result of other approach.

**Thermal Design**

Figure 6 shows the cross section of the heat conduction model. The heat source is regarded as only environment at the ambient temperature around the valve. In reality, the energized coil generates the heat, but it is negligible since the actuator consumes no electric power during the steady state due to the latch-mechanism. The heat conductance $U_c$ at the part covered with the coil is approximated by;

$$\frac{1}{U_c} = \frac{1}{2\pi\alpha} \ln \frac{R_3}{R_1} + \frac{1}{2\pi\alpha} \ln \frac{R_5}{R_4} + \frac{1}{2\pi\alpha} \ln \frac{R_7}{R_6} + \frac{1}{2\pi\alpha} h_l,$$ \hspace{1cm} (7)

where insignificant terms are neglected. $h_l$ is the heat transfer coefficient of the cold air through the valve and

![Figure 4 Simplified block diagram of the magnetic circuit](image)

![Figure 5 Switching characteristics calculated by the classical method](image)
\( \lambda_a \) and \( \lambda_v \) are the thermal conductivities of the air and the vacuum layer. \( h_i \) can be expressed in terms of the Nusselt number that is estimated by a certain function of the Reynolds and the Prandtl numbers [4]. Similarly, \( U_b \), the thermal conductance at the body part, and \( U_{ni} \), the non-insulated part at the both ends of the body and the middle of the inner sleeve to which the yoke-B connects are given by:

\[
\begin{align*}
\frac{1}{U_b} &= \frac{1}{2\pi \lambda_a} \ln \frac{R_3}{R_2} + \frac{1}{2\pi \lambda_v h_i}, \\
\frac{1}{U_{ni}} &= \frac{1}{2\pi \lambda_a} \ln \frac{R_{ni2}}{R_{ni1}} + \frac{1}{2\pi \lambda_v h_i}.
\end{align*}
\]

where \( \lambda_a \) is the thermal conductivity of the magnetic stainless steel. The heat balance relation is expressed by:

\[
FpC_p (T_{IN} - T_{OUT}) = (U_b l_b + U_c l_c + U_{ni} l_{ni}) (T_i - T_o),
\]

where, \( F \), \( p \), \( C_p \) are the flow rate, the density and the specific heat of the cold air, respectively. \( T_i \) is the cold air temperature and \( T_o \) is the ambient temperature. \( l_b \), \( l_c \), and \( l_{ni} \) represent the axial length of the body, the coil and the non-insulated parts, respectively (see Figure 2).

Using \( T_i \) as the average temperature of the inlet: \( T_{IN} \) and the outlet: \( T_{OUT} \),

\[
T_i = \frac{T_{IN} + T_{OUT}}{2},
\]

the air temperature at the outlet is roughly approximated by:

\[
\begin{align*}
T_{IN} &= \left( U_b l_b + U_c l_c + U_{ni} l_{ni} \right) \left( \frac{T_{IN}}{2} - T_o \right) \\
T_{OUT} &= \frac{1}{2} \left( 1 + 1 \right) \frac{U_b l_b + U_c l_c + U_{ni} l_{ni}}{FpC_p}.
\end{align*}
\]

Since these basic design approaches consume less time to get the results compared with numerical methods such as FEM, they have advantage to get the initial dimensions of each part promptly, but generally have less accuracy.

**ADVANCED ACTUATOR DESIGN**

The rough model of which the initial dimensions had been determined in the basic design process was modified by means of FEM analyses. In electromechanical part, the magnetic flux density distribution, especially at the yoke connection points to the inner sleeve, was evaluated by the magnetic field analysis software, Maxwell (Ansoft: axis-symmetry 3D), which could take the fringing flux paths and the partial magnetic saturation into consideration. Figure 7 shows the magnetic flux density distribution at the condition that the plunger is in the closest position to the stator and the coil is energized by the positive current, in which the maximum flux flow appears in the magnetic circuit. It is confirmed that the thickness at both the connection points are sufficient magnetically since each magnetic flux density is approximately below 1.1 T that is regarded to be under the magnetic saturation. Figure 8 shows the calculated static characteristics of the electromagnetic attracting force. The latching force that keeps the plunger on the stator is expressed by the force difference between the PM alone and the spring load curves at \( l_{gap} = 0 \) mm in this figure.

In the thermal evaluation, the temperature distribution in the steady state was calculated by the FEM software, ANSYS (ANSYS Inc). Figure 9 indicates that the yoke connection points have high thermal resistance because the high temperature region does not bulge deeply into the inside of the valve through the points. Though the ends of the body are not covered with the vacuum insulation layer and have high temperature region close
to the conduit inside the valve, it is negligible since the flexible pipes with the vacuum insulation layer are connected there in the actual application.

**PERFORMANCE TEST**

Figure 10 shows the performance test apparatus. The cold airflow generated at the chiller is conducted to a series of the five valves through the pipe and the temperatures are measured at the both ends of the series. This serial connection can enlarge the S/N ratio in the measurement of the temperature difference. The airflow line except the valves is covered with the insulating material, and the valves are exposed to the ambient temperature. The insulation performance is evaluated by the thermal transmittance that is the reciprocal sum of the separate series resistivities. Using the temperature difference per valve, which is estimated by linear interpolation of the measured temperature difference, and some thermophysical properties in Table 2, the experimental thermal transmittance $K$ is calculated by

$$K = \frac{F_d C_p (T_{IN} - T_{OUT})}{S(T_i - T_o)}, \quad (13)$$

where $S$ is the area of the heat conductive surface. The smaller $K$ means that the valve has the higher thermal
resistance and the better insulation performance. Figure 11 shows the comparison of the developed valve on the thermal transmittance with the non-insulated conventional valve of which size is much the same. It is confirmed that the thermal transmittance of the developed valve is about one thirtieth of the conventional under the condition of the inlet temperature of -12.2°C and the ambient temperature of 20.5°C.

The latch-mechanism is evaluated by the comparison on the temperature rise of the cold air with the same insulated valve in which PM is removed and the coil is energized by the conventional voltage pattern. Table 3 shows the measured temperature rise of the cold air at 30 minutes after energizing the coil in rated voltage of 24V. The heat generation at the coil has a harmful influence on preventing the air temperature rise. On contrary, the latch-mechanism reduces the heat generation at the coil and keeps the air temperature rise within 0.7°C. This indicates that only vacuum insulation layer is insufficient for preventing the air temperature rise, but the combination of the insulation layer and latch-mechanism is effective for it. Just for reference, the air temperature rise calculated by eq.(12) is 0.4°C that is error of less than 0.3°C to the measured one (0.7°C).

CONCLUSION

The electro-pneumatic valve that has the thermal insulation function has been developed for the dry cutting/grinding system that utilizes the cold airflow instead of the cutting oil. It has the vacuum insulation layer inside for preventing the heat inflow to the cold air and the latch-mechanism for reducing the heat generation at the coil. Its thermal transmittance is about one thirtieth of the conventional.

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