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Design Parameter Study of a Permanent Magnet Biased Magnetic Actuator for Improving Stiffness and Linearity

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Abstract

This paper presents a study on the design parameters of a permanent magnet (PM) biased magnetic actuator (MA) for improving stiffness and linearity of the system by using a dimensional analysis. To reduce the number of parameters and to generalize the results for similar systems, the design parameters were non-dimensionalized by significant variables characterizing the system. For the study, a 1-DOF PM-biased MA was built and the magnetic circuit model including leakage paths and core material reluctances was set up. The dimensional analysis shows that the dimensionless permanent magnet thickness is the key parameters for the linearity of the magnetic force and constancy of coil inductance and PM magnetic flux and that the non-dimensional leakage resistance is a main factor for the bound of the efficiency and the linearity.

Keywords: Magnetic actuator; Permanent magnet; Nondimensionalization; Design parameter

1. Introduction

The PM-biased MA that uses the flux of PM instead of the flux of the bias current has strong advantages with respect to energy saving, core iron loss and actuator size. The PM-biased MA is mainly applied to a radial bearing for high speed rotors (Murphy et al., 2004; Meeks et al., 1994), and is occasionally combined with an axial bearing (McMullen et al., 2000). It is often used as an actuator for precision positioning (Molenaar et al., 1997; Lee et al., 2002; Kim and Gweon, 2005), and as a vibration isolator (Lee and Lee, 2006) or electro-magnetic exciter (Lequesne, 1990; Oberbeck and Ulbrich, 2002).

According to research works, PM-biased MAs can show better linear characteristics throughout the operation range than the conventional electromagnetic actuator. Figure 1 shows the 1-DOF PM-biased MA (Lee et al., 2002; Kim and Gweon, 2005) consists of a center core wound by serially connected upper and lower coils and two side core connected to centers core by PMs. In the concept of the PM-biased MA, the electromagnet flux does not pass through the PM, and the total air gap in the EM flux path is constant. Therefore, demagnetization is prevented and coil inductance perturbation by actuator position variation is small. Resulting magnetic force of the actuator becomes also more linear with displacement and current. This feature enables a micro positioning without control performance degradation in a wide operation range and enables zero power control to tolerate a large static force (Mizuno et al., 1998).

Some applications such as a vibration isolator, electro-magnetic exciter, position compensator in maglev stage and unbalance controller for high-speed rotors require a wide operation range. To date, the full

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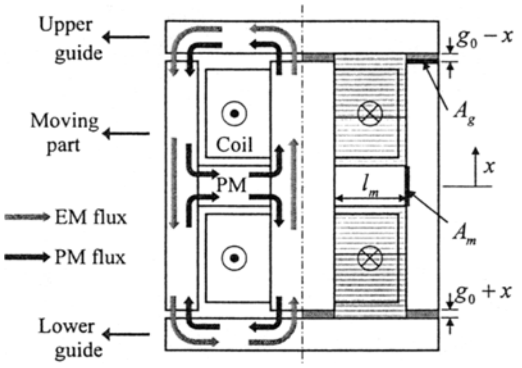

Fig. 1. The MA concept (left side) and divisions of simplified magnetic flux resistances considering leakage. (right side)

range performance of the PM-biased MA has not been fully investigated, and thus the control performance bound due to the linearity error cannot be evaluated accurately. Previous studies (Sortore et al., 1990; Pichot et al., 2004) have focused on the characteristics of the PM-biased MAs at nominal displacement and current, and frequently neglected the magnetic flux leakage that may significantly affect the linear characteristics of the magnetic force. Finite element analysis is a common method used for calculating the properties of an actuator and can easily consider the leakage flux, magnetic flux saturation, hysteresis, nonlinear B-H relation and eddy current effect. But FE analysis requires much calculation time and lacks in generality for designs of various dimensions. Therefore it is difficult and time-consuming process to determine parameters guaranteeing the high stiffness, linearity of magnetic force according to displacement and current, and also constancy of coil inductance and PM magnetic flux.

In this paper, a dimensional analysis is suggested to find main design parameters for improving the stiffness and linearity. We will define the scaling parameters of the 1-degree-of-freedom (DOF) PM-biased MA, non-dimensionalize the simplified PM-biased MA model, and clarify the dimensionless design parameters that affect the linearity characteristics as well as displacement stiffness and current gain. These dimensionless design parameters can grant generality to the similar PM-biased MA system design.

2. Magnetic circuit model

Figure 1 shows a 1-DOF PM-biased MA (Lee et al., 2002; Kim and Gweon, 2005) used for the dimensional analysis. It is composed of an assembled moving part of cores, two PMs and serially-connected coils between the upper and lower fixed guides. The PMs are positioned such that the same magnet poles face each other. Coils are wound around the center core. The PM magnetic flux and electromagnet magnetic flux are formed symmetrically along the black and grey arrows respectively in the left side of Fig. 1. The magnetic force of the actuator results from the difference of two magnetic field densities between the guides and the moving part.

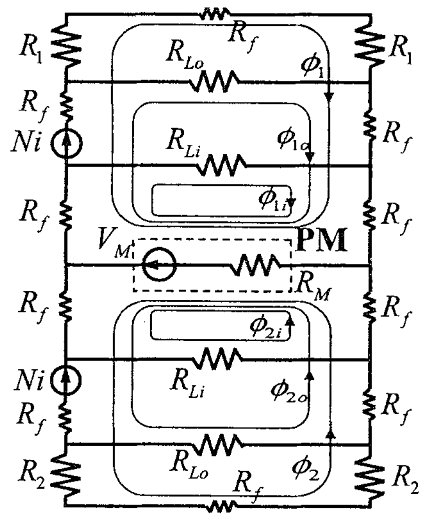

Fig. 2. Equivalent magnetic circuit of half model. (right side of Fig. 1)

Since the actuator in Fig. 1 is symmetric, we modeled only half of the actuator. Because the actual magnetic flux paths are very complicated, a simplified magnetic circuit model shown in Fig. 2 was introduced to study design parameters. Magnetic resistance R_M of PM and magnetic resistance R_1, R_2 of the narrow air gaps between the I-shaped cores and guides are dominant resistances. Two leakage paths that pass through each coil are introduced. PM is simply described as magnetomotive force V_M and resistance R_M since the B-H relation of PM is linear around the operating point, and most designs show a small flux variation of PM.

For simplicity, we ignored nonlinear effects such as magnetic flux saturation, hysteresis, nonlinear B-H relation and eddy current effect. Then, the magnetic circuits of the flux loops in Fig. 2 were composed from Ampere's loop law. (Roters, 1941)

$$\begin{aligned}
\phi_1 : Ni &= 2R_1\phi_1 + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) \\
&\quad -V_M + R_{f1}\phi_1 + R_{f2}\cdot(\phi_1+\phi_{1o}) \\
&\quad + R_{f3}\cdot(\phi_1+\phi_{1o}+\phi_{1i}) \\
\phi_2 : -Ni &= 2R_2\phi_2 + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) \\
&\quad -V_M + R_{f1}\phi_2 + R_{f2}\cdot(\phi_2+\phi_{2o}) \\
&\quad + R_{f3}\cdot(\phi_2+\phi_{2o}+\phi_{2i}) \\
\phi_{1o} : Ni &= R_{Lo}\phi_{1o} + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) \\
&\quad -V_M + R_{f2}\cdot(\phi_1+\phi_{1o}) + R_{f3}\cdot(\phi_1+\phi_{1o}+\phi_{1i}) \\
\phi_{2o} : -Ni &= R_{Lo}\phi_{2o} + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) \\
&\quad -V_M + R_{f2}\cdot(\phi_2+\phi_{2o}) + R_{f3}\cdot(\phi_2+\phi_{2o}+\phi_{2i}) \\
\phi_{1i} : 0 &= R_{Li}\phi_{1i} + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) \\
&\quad -V_M + R_{f3}\cdot(\phi_1+\phi_{1o}+\phi_{1i}) \\
\phi_{2i} : 0 &= R_{Li}\phi_{2i} + R_M\cdot(\phi_1+\phi_2+\phi_{1o}+\phi_{2o}+\phi_{1i}+\phi_{2i}) - V_M \\
&\quad + R_{f3}\cdot(\phi_2+\phi_{2o}+\phi_{2i})
\end{aligned} \tag{1}$$

In Eq. (1), N is coil turn and i is coil current. Except iron resistance R_{f1}, R_{f2} and R_{f3}, subscript 1 and 2 mean upper part and lower part, respectively. Subscript L, M, o and i mean leakage, PM, outer leakage path and inner leakage path, respectively.

The resistances R_1 and R_2 of dominant air gaps are the functions of actuator displacement x, as shown in Eq. (2).

$$R_1 = \frac{g_0 - x}{\mu_0 A_g}, \quad R_2 = \frac{g_0 + x}{\mu_0 A_g} \tag{2}$$

If we define the relative permeability μ_m of PM around the operating point, PM resistance R_M can be defined as Eq. (3).

$$R_M = \frac{l_m}{\mu_0 \mu_m A_m} \tag{3}$$

We assume constant magnetic resistances, excluding the significant air gap resistances R_1 and R_2. Then the magnetic force of the half actuator can be defined as Eq. (4). The magnetic force is the function of magnetic fluxes through dominant air gaps.

$$F = \sum\left(-\frac{1}{2}\phi^2\frac{dR}{dx}\right) = \frac{1}{\mu_0 A_g}\left(\phi_1^2 - \phi_2^2\right) \tag{4}$$

For effective control of coil current, coil inductance should be less sensitive to displacement. So the constancy of inductance is one of the important design objects. Inductance of the half actuator can be defined as Eq. (5).

$$L = N\frac{d}{di}(\phi_1 + \phi_{1o}) - N\frac{d}{di}(\phi_2 + \phi_{2o}) \tag{5}$$

A variation of magnetic flux through PM induces the demagnetization of PM, which results to performance decrease of the PM actuator. A magnetic flux of PM is shown in Eq. (6), in which PM flux ϕ_m includes the leakage magnetic flux.

$$\phi_m = \phi_1 + \phi_2 + \phi_{1o} + \phi_{2o} + \phi_{1i} + \phi_{2i} \tag{6}$$

3. Scaling parameters

Scaling parameters are characteristic design parameters of the system like magnetic force, magnetic flux, reference air gap and reference coil current. They are frequently specified in order to satisfy design objectives. Scaling parameters are defined in an ideal condition, where leakage and iron's reluctance are ignored: $R_{Lo}=R_{Li}=\infty$, $\varphi_{1o}=\varphi_{1i}=\varphi_{2o}=\varphi_{2i}=0$, $R_{f1}=R_{f2}=R_{f3}=0$. These scaling para-meters are not affected by the complexity and structure of the analysis model. The ideal magnetic circuit equations can be summarized as Eq. (7).

$$\begin{aligned}
\phi_1 &: Ni = 2R_1\phi_1 + R_M\cdot(\phi_1+\phi_2) - V_M \\
\phi_2 &: -Ni = 2R_2\phi_2 + R_M\cdot(\phi_1+\phi_2) - V_M
\end{aligned} \tag{7}$$

Using these equations, scaling parameters were calculated and defined in Table 1.

Table 1. Scaling parameters and their meaning.

Dimension	Scaling parameters	Definition and interpretation
Displacement	g_0	Significant air gap
Magnetic resistance	$R_0 = \frac{g_0}{\mu_0 A_g}$	Magnetic resistance (R_1, R_2) of significant air gap at nominal displacement ($x=0$)
Magnetic flux	$\Phi_0 = \frac{V_M}{R_0 + R_M}$	Magnetic flux (ϕ_m) of PM at nominal state ($x=i=0$)
Current	$I_0 = \frac{R_0\Phi_0}{N}$	Current to make $\phi_1=0$ or $\phi_2=0$ at $x=0$ Current to make $\phi_1=\phi_2$ and $F=0$ at $x=\pm g_0$
Magnetic force	$F_0 = \frac{\Phi_0^2}{\mu_0 A_g}$	Dimensionless displacement stiffness $k_\xi=1$ and dimensionless current gain $k_\eta=1$ at nominal state ($x=i=0$)
Inductance	$L_0 = \frac{N^2}{R_0}$	Coil inductance at nominal state ($x=i=0$)

4. Dimensionless form of the magnetic circuit model

To non-dimensionalize Eq. (1), we divide Eq. (1) by NI_0 ($=R_0\Phi_0$). Dimensionless variables are defined in Eqs. (8)~(13).

$$\frac{x}{g_0}=\xi,\ \frac{i}{I_0}=\eta \tag{8}$$

$$\frac{\phi_1}{\Phi_0}=\psi_1,\ \frac{\phi_2}{\Phi_0}=\psi_2,\ \frac{\phi_{1o}}{\Phi_0}=\psi_{1o},\ \frac{\phi_{2o}}{\Phi_0}=\psi_{2o},$$
$$\frac{\phi_{1i}}{\Phi_0}=\psi_{1i},\ \frac{\phi_{2i}}{\Phi_0}=\psi_{2i} \tag{9}$$

$$\frac{R_1}{R_0}=1-\xi,\ \frac{R_2}{R_0}=1+\xi \tag{10}$$

$$\frac{R_{Lo}}{R_0}=r_{Lo},\ \frac{R_{Li}}{R_0}=r_{Li},\ \frac{R_{f1}}{R_0}=r_{f1},\ \frac{R_{f2}}{R_0}=r_{f2},$$
$$\frac{R_{f3}}{R_0}=r_{f3} \tag{11}$$

$$\frac{R_M}{R_0}=\frac{1}{\mu_m}\cdot\frac{l_m}{g_0}\cdot\frac{A_g}{A_m}=\tau \tag{12}$$

$$\frac{V_M}{R_0\Phi_0}=1+\frac{R_M}{R_0}=1+\tau \tag{13}$$

The magnetic resistances R_1 and R_2 of the air gap between core and guides are defined as a function of the dimensionless displacement ξ. PM magnetic resistance R_M is converted into dimensionless magnet thickness τ, which consists of the PM relative permeability μ_m, PM thickness l_m, PM pole area A_m, air gap g_0 and dominant pole area A_g. PM magnetomotive force V_M is a function of the variable τ as described in Eq. (13). In dimensionless form, the only characteristic variable of PM is τ.

Then, a dimensionless magnetic circuit equation is constructed, and all magnetic fluxes can be calculated as follows.

$$\begin{aligned}
\psi_1 &: \eta=2(1-\xi)\psi_1+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f1}\psi_1+r_{f2}(\psi_1+\psi_{1o})+r_{f3}(\psi_1+\psi_{1o}+\psi_{1i})\\
\psi_2 &: -\eta=2(1+\xi)\psi_1+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f1}\psi_2+r_{f2}(\psi_2+\psi_{2o})+r_{f3}(\psi_2+\psi_{2o}+\psi_{2i})\\
\psi_{1o} &: \eta=r_{Lo}\psi_{1o}+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f2}(\psi_1+\psi_{1o})+r_{f3}(\psi_1+\psi_{1o}+\psi_{1i})\\
\psi_{2o} &: -\eta=r_{Lo}\psi_{2o}+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f2}(\psi_2+\psi_{2o})+r_{f3}(\psi_2+\psi_{2o}+\psi_{2i})\\
\psi_{1i} &: 0=r_{Li}\psi_{1i}+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f3}(\psi_1+\psi_{1o}+\psi_{1i})\\
\psi_{2i} &: 0=r_{Li}\psi_{2i}+\tau\cdot(\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i})\\
&\quad -(1+\tau)+r_{f3}(\psi_2+\psi_{2o}+\psi_{2i})
\end{aligned} \tag{14}$$

Meanwhile, dimensionless magnetic force f, dimensionless inductance l and PM magnetic flux ψ_m can be obtained by Eqs. (15)~(17), respectively.

$$f=\frac{F}{F_0}=\sum\left(-\frac{1}{2}\psi^2\frac{dr}{d\xi}\right)=\psi_1^2-\psi_2^2 \tag{15}$$

$$l=\frac{L}{L_0}=\frac{d}{d\eta}(\psi_1+\psi_{1o}-\psi_2-\psi_{2o}) \tag{16}$$

$$\psi_m=\frac{\phi_m}{\Phi_0}=\psi_1+\psi_2+\psi_{1o}+\psi_{2o}+\psi_{1i}+\psi_{2i} \tag{17}$$

In order to investigate the linearity of the magnetic force, dimensionless displacement stiffness k_ξ and dimensionless current gain k_η are calculated as follows.

$$k_\xi=\frac{df}{d\xi},\ k_\eta=\frac{df}{d\eta} \tag{18}$$

The analysis results will be calculated according to dimensionless displacement ξ and dimensionless current η.

5. Example dimensional analysis result of a test rig

Before the linearity analysis, we examined the tendencies of the coil inductance, PM magnetic flux, and the magnetic force of the PM-biased MA according to dimensionless displacement ξ and dimensionless current η. Because the maximum moving range is g_0 and current I_0 is enough for initial levitation, we set the full range of displacement ξ and current η from -1 to 1.

We used design coefficients of the test rig (Lee et al., 2002) in Eq. (19) as an example. The calculated magnetic force using Eq. (14) was in good agreement with the experiment result of the 1-DOF test rig.

$$\begin{aligned}
&g_0=0.315mm,\ I_0=3.71A,\\
&F_0=77.3N,\ L_0=1.77mH\\
&r_{Lo}=7.87,\ r_{Li}=7.41,\\
&r_{f1}=0.0434,\ r_{f2}=0.0259,\\
&r_{f3}=0.0246,\ \tau=15.5
\end{aligned} \tag{19}$$

Dimensionless inductance l is calculated by Eq. (16). Its variation according to dimensionless displacement are shown in Fig. 3 and compared with inductance variation of conventional electromagnetic (EM) actuator. In the PM-biased MA, the constant total air gap in the electromagnet flux path of Fig. 1 reduces the inductance variation. Inductance of the test rig shows 43% variation as compared with the value of nominal state ($\xi=\eta=0$). We suppose the equivalent electromagnetic actuator with no PM. It has separated upper electromagnet and lower electromagnet that have nominal air gap g_0, coil turn N, current i, equivalent leakage and iron resistance. Then coil inductances of two electromagnets show 1528% variation from nominal value in the full range.

PM magnetic flux ψ_m variation according to dimensionless displacement ξ and dimensionless current η are calculated with 0.4 η intervals by Eq. (17) and are shown in Fig. 4. PM magnetic flux of the test rig shows 12% variation as compared with the value of nominal state ($\xi=\eta=0$). Due to the different flux paths of the PM and electromagnet of Fig. 1, the variation of the PM magnetic flux is very small. Thus performance deterioration by demagnetization of PM is prevented.

The dimensionless magnetic force f according to displacement and current are calculated by Eq. (15) and are shown in Figs 5 and 6. At the nominal state ($\xi=\eta=0$), the magnetic force is zero. The variation rates of this force according to displacement and current, which is called the displacement stiffness and the current gain, are usually minimum values at the nominal state. If the dimensionless PM thickness τ would become large in the ideal condition above, the dimensionless magnetic force would be completely linear and both the displacement stiffness k_ξ and the current gain k_η would be one. As the dimensionless PM thickness τ is constrained and inevitable leakage flux exists, the magnetic force is somewhat nonlinear. When both the displacement and the current are positive or negative, the magnetic force is more nonlinear and the displacement stiffness k_ξ and the

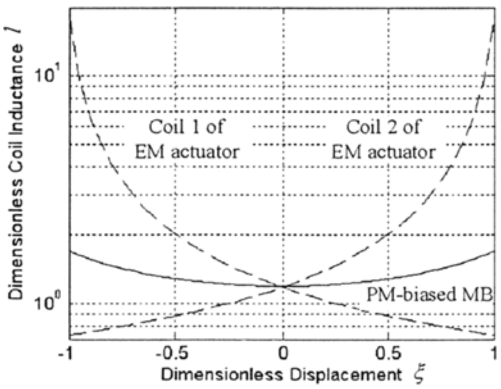

Fig. 3. Displacement-inductance graph of the test rig.

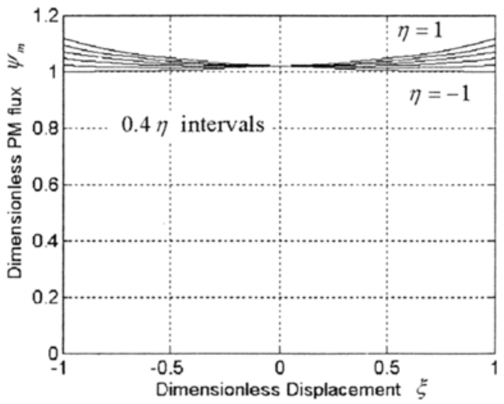

Fig. 4. Displacement-PM magnetic flux graph of the test rig.

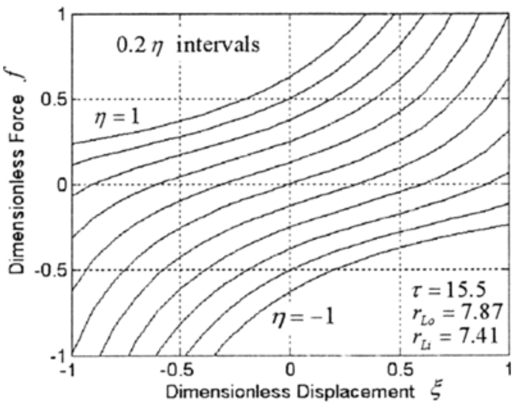

Fig. 5. Displacement-force graph of the test rig.

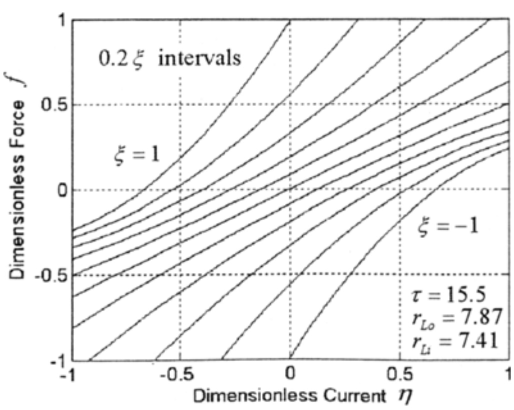

Fig. 6. Current-force graph of the test rig.

current gain k_η become larger than nominal values. However, this type of operation condition is not usual in normal servo control and the control around $f = 0$ is more important. The two parameters k_ξ and k_η will not vary greatly in actual control. Thus, Figs. 5 and 6 do not show the area that the absolute value of dimensionless magnetic force f is more than one.

When the operating ranges of displacement ξ and current η were reduced, the linearity was considerably improved, as shown in the analysis results. Even in the full range, its linearity was much better than that of an electromagnetic actuator.

6. Effects of dimensionless design parameters

The representative leakage resistance r_L is defined as a parallel connection of outer leakage resistance r_{Lo} and inner leakage resistance r_{Li}. Because the ratio of r_{Lo} and r_{Li} does not affect the analysis results by much, we set r_L=0.5r_{Lo}=0.5r_{Li}. The small representative leakage resistance r_L means large leakage. The value of r_L varies from 1 to 8 in this paper and these values are typical in the design of the PM-biased MA.

The value of dimensionless PM thickness τ varies from 1 to 200 in this paper. If τ is less than 1, large fluctuation of PM magnetic flux may result in demagnetization of PM. Large τ makes the ratio of the actuator force and size small and τ of more than 200 is unrealistic.

The iron resistance reduced the overall k_ξ and k_η but slightly improved the force linearity because it enlarged the effective air gaps. The iron resistance was not considered in the linearity analysis of other variables.

We calculated the nominal value of k_ξ and k_η according to the leakage resistance r_L and PM thickness τ, as shown in Figs. 7 and 8, respectively. Smaller leakage, that is a larger leakage resistance, naturally increased the k_ξ and k_η but a larger PM thickness reduced the k_ξ and k_η instead. Small leakage and small PM thickness are better choice for large dimensionless displacement stiffness and dimensionless current gain. In other words, PM magnetic flux and electromagnetic flux are used more effectively in this condition.

We define the linearity of the displacement stiffness and the current gain as the maximum relative variation based on the nominal value in the full range: $-1 \le \xi \le 1$ and $-1 \le \eta \le 1$, as shown in Figs. 9 and 10. Smaller leakage and larger PM thickness reduces the ratios, which means better linear characteristics of magnetic force.

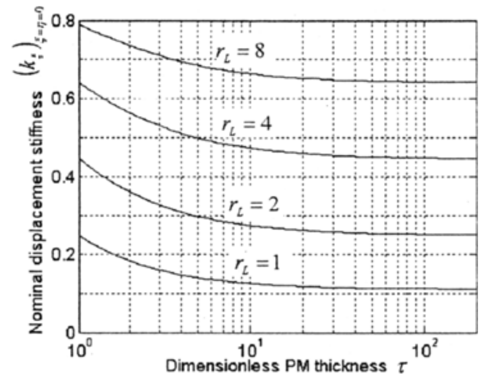

Fig. 7. Nominal dimensionless displacement stiffness vs. PM thickness and leakage.

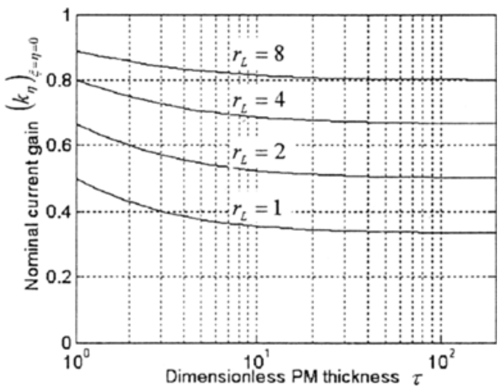

Fig. 8. Nominal dimensionless current gain vs. PM thickness and leakage.

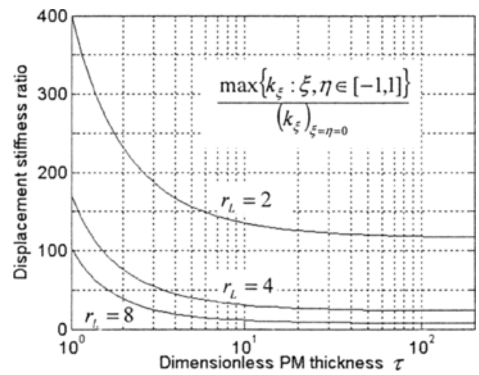

Fig. 9. Maximum/nominal ratio of displacement stiffness vs. PM thickness and leakage.

We calculate the nominal value and the maximum value of inductance according to the leakage and PM thickness, as shown in Fig. 11. The nominal value of

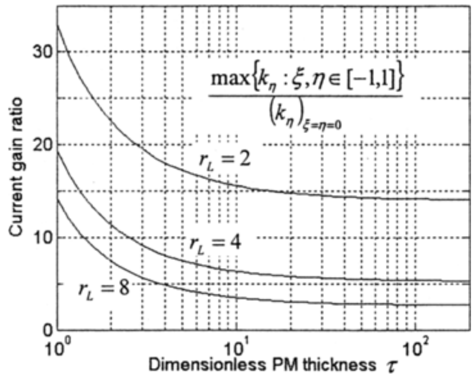

Fig. 10. Maximum/nominal ratio of current gain vs. PM thickness and leakage.

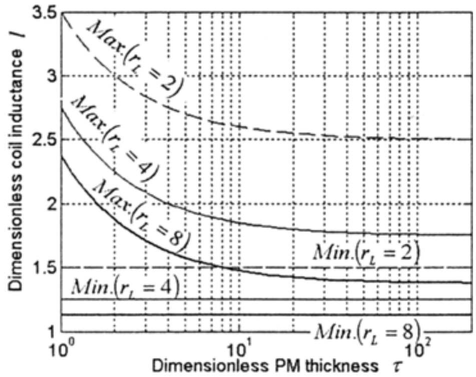

Fig. 11. Maximum and minimum values of coil inductance vs. PM thickness and leakage.

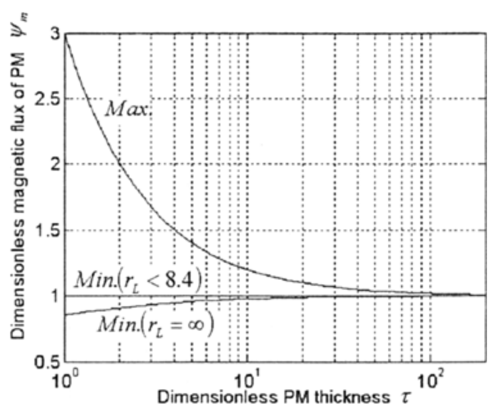

Fig. 12. Maximum and minimum values of PM magnetic flux vs. PM thickness and leakage.

inductance is the function of the leakage and is constant according to PM thickness. The maximum value declines as the leakage r_L and PM thickness increase. Larger leakage resistance r_L and PM thickness τ make smaller inductance variation that is the gap between the maximum and minimum values. In the case of the PM magnetic flux of the full operating range, as shown in Fig. 12, the maximum value is constant according to leakage r_L and the minimum value decreases slightly over r_L=4.2. PM thickness τ is the most important factor to adjust the variance of PM magnetic flux ψ_m. In the reduced operating range, not shown in the figure, the maximum and minimum values decrease as leakage r_L increases and the gap between those values converges.

7. Design suggestions of the PM-biased MA

From results of previous paragraph, it can be concluded that the dimensionless PM thickness τ contributes to linearity but the improvement effectiveness decreases by over 10^1 and the bound of linearity is determined by leakage. Leakage r_L, which is the inevitable loss, severely degrades the linearity. For both high current gain and force linearity, small leakage and dimensionless PM thickness τ of over 10^1 are recommended. Since improvement effects of PM thickness τ of over 10^1 are trivial, limited actuator size should be considered in the design of PM thickness. This condition is also applied to constancy of the coil inductance and the PM magnetic flux. And reducing the operating range in dimensionless value improves the linearity performance.

Materials of PM and iron core are decided in advance. As the ratio of air gap A_g and PM pole area A_m is related to magnetic flux density of iron core, PM thickness l_m is a main factor to adjust the dimensionless PM thickness τ. Considering dimensionless PM thickness τ of over 10^1, Eq. (20) is recommended as PM thickness l_m.

$$l_m \geq 10 \cdot \mu_m g_0 \frac{A_m}{A_g} \tag{20}$$

The region, in which magnetic flux leakage arise, can be reduced to the coil-wound region. In order to make the leakage resistance r_L is large, the leakage region is short and flat. Thus, the profile of the actuator will be short and flat.

8. Conclusions

We generalized the design parameters of 1-DOF

PM-biased MA for linearity characteristics via the non-dimensionalization. This type of magnetic actuator has better linearity characteristics than the conventional electromagnetic actuator. Defined scaling parameters are fundamental design parameters. Dimensionless PM thickness and leakage as well as iron resistance are the most important variables affecting linearity performance. For high current gain, magnetic force linearity, constant inductance and low demagnetization, we suggest

- Dimensionless PM thickness τ of over 10^1
- Minimum leakage; short and flat actuator profile

In an extension of this analysis, the design process of a more complicated PM-biased MA system can be realized by using dimensional similarity.

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