Design and Analysis of a Lorentz Linear Motor for Precision Vibration-Isolation[1]

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Abstract: This paper describes a design approach to Lorentz motors that serve as active damping component applicable in dynamic vibration isolators used for integrated circuit(IC) equipments. To satisfy the demand of high force density in constrained space and high current accuracy of motor drive for active damping, an analytical layer model with proper simplifications is employed to get preliminary dimensions, then a 3-D finite element(FE) model is built and analyzed to obtain a further optimal result. Finally a motor drive including current regulation circuit, H-bridge drive circuit, LC filter circuit and the current feedback circuit is developed. The performance of the motor is evaluated by experiments.

1 Introduction

Last decade witnesses a significant progress in semiconductor industry. The highly developed technology and high-precision manufacturing of IC industry make its machining precision and detection results ultra-high sensitive to the vibration, a small amount of which may introduce undesirable noise and affects the manufacturing accuracy. As a result, vibration isolation has been being an important research topic in IC industry [HL94]. The system and the excitation force of IC equipment often operates at varying frequencies, so ultra-precision vibration isolators adopting active isolation technique are the most common solution to vibration problems[CF05]. Air-cored Lorentz linear motors, are characterized by direct drive, high speed, high acceleration, high positioning precision, fast dynamics and low force pulsation, which make them easy to maintain, so they are well-recognized to be an appropriate choice as active dynamic actuators in precision vibration isolation systems [GP00][KJ04].

A kind of active dynamic isolator IC manufacturing using air-cored Lorentz motor for is introduced in this paper, shown in Figure 1. The dual-chamber pneumatic spring

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provides high bearing capacity (>10000N) and isolate high frequency vibration. The motor works as a sky hook damper that introduces absolute damping into the system, providing small but fast damping force (<100N) responding to the velocity signal of low frequency vibration.

The active damping of the isolator calls for a near-zero stroke (≤ 20μm) but high force density in restricted space. In this paper, within the volume of 160×80×70mm^3, the force constant of object motor must reach the amount of 70N/A, which is almost double that of a traditional slotless Lorentz linear motor under the same condition, meanwhile the constant is strongly required with high linearity. As a result, the force generation capability of the object motor should be elaborate. In this case, an optimization design method for the object motor is essential[IS07][OK06][JC10]. The motor drive also must be proper designed to meet high bandwidth and current accuracy.

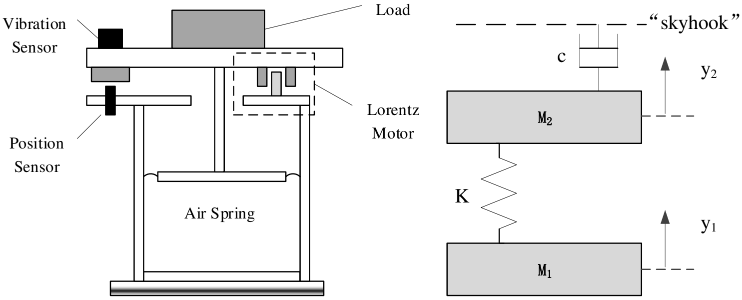

Figure 1: Structure of the active dynamic isolator and its schematic

2 Motor Design

2.1 Analytical Model and FE Analysis

The Lorentz motor in this paper consists of a primary located between two secondaries. Each secondary consists of rare earth permanent magnet (PM) poles mounted on a back iron. This arrangement provides two air gaps with small length. The primary is an air cored coil fixed in an aluminum alloy box.The lack of an iron core with teeth and slots and the makes it possible to employ a simple physical layer model to provide a basis for formulation of the motor [IS07], as shown in Figure 2, on the assumption that:

1. The air-gap magnetic field is 2D plane field.
2. The whole model is linear.
3. The permeability of iron layers is infinity.
4. No external magnetic field interference.

The model consists of two iron layers, two permanent magnet layers and an air layer; representing the back irons, PM poles and the air gaps plus the primary winding. The fundamental and harmonic component of the PM field can be obtained from Maxwell equations in the different layers. The maximum value of the PM flux under each pole is related to the fundamental component, so by minimizing the total harmonic distortion of the PM field the force pulsations can be minimized and the utilization of PM fields can be maximized.

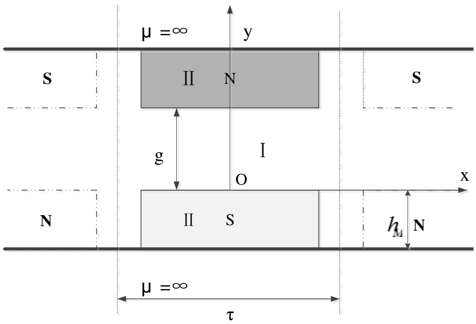

Figure 2: Layer model of air-cored Lorentz linear motor

The total harmonic distortion is given by

$$
HD_{total} = \frac{\sqrt{\sum_{n=3,5,...}^{\infty} \frac{n\pi}{\tau}\left(C_1 e^{\frac{n\pi g/2}{\tau}} + C_2 e^{\frac{-n\pi g/2}{\tau}} \right)^2}}{\frac{\pi}{\tau}\left(C_1 e^{\frac{\pi g/2}{\tau}} + C_2 e^{\frac{-\pi g/2}{\tau}} \right)} \tag{1}
$$

where

$$
\begin{cases}
C_1 = \dfrac{\dfrac{4B_r\tau}{n^2\pi^2}\sin(\dfrac{\eta n\pi}{2})e^{\frac{-2n\pi g/2}{\tau}}}{(e^{\frac{-2n\pi g/2}{\tau}}+1)+\left(\dfrac{\mu_M(-e^{\frac{-2n\pi g/2}{\tau}}+1)(e^{\frac{-2n\pi h_M}{\tau}}+1)}{\mu_0(e^{\frac{-2n\pi h_M}{\tau}}-1)}\right)} \\
C_2 = C_1 e^{\frac{2n\pi g/2}{\tau}}
\end{cases} \tag{2}
$$

Br is the remanence magnetic flux density, g is the air gap length h_M is the magnet height, τ is the pole pitch and η is the ratio of the magnet width to pole pitch.

As the stroke of the motor is near zero (≤ 20μm) and for control conveniently, the motor is designed to be a single-phase DC-PM.

From Eqs. (1), preliminary optimal motor dimensions are obtained with the help of Matlab with proper constraints. Then a 3-D FE model based on the preliminary result for further optimal design is built with the help of Ansoft, taking material nonlinearity, end effect and asymmetrical winding into account.

The 3D FE model uses volume current method and quadratic interpolation to approach field quantity in each element. The primary coil is equivalent to current density. Since there is flux leakage and end effect, a balloon boundary is adopted as solution region to simulate real magnetic fields. The whole model is divided into about 30,000 elements.

Figure 3 shows the analysis result of flux density distribution with the 3-D FE model. The flux density in the middle of air gap obtained from the analysis result well agrees with the analytical result, so the accuracy of the analytical model is validated.

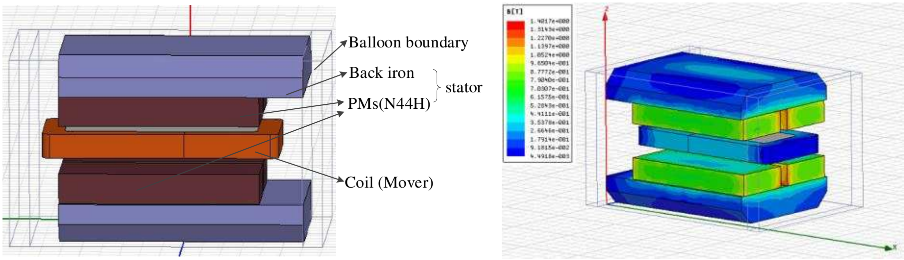

Figure 3: FE model of air-cored Lorentz linear motor and analysis results

The FE analysis results also help get the optimum working area of the primary, which is simply considered as an air layer with the air gap, adjust the PM dimensions and the air gap, optimize the inductance of coil and check whether the force constant attain the design target. With the 3-D FE analysis, further optimal motor dimensions are obtained.

2.2 Motor drive

The motor drive is designed based on PII control algorithm to provide the motor with fast following response and high control accuracy, the system diagram is shown in Figure 4.

In Figure 4, current regulator (CSR) output reference voltage $u_{CSR}(s)$ based on the voltage deviation $u_{\varepsilon}(s)$. Then $u_{CSR}(s)$ is sampled and converted into digital signals by digital converting unit ADC1 of microcontroller STM32. The signal is processed and turned into PWM wave, then output to H-Bridge power convertor. The PWM driving signals output to Lorentz motor through LC filter circuit. Voltage signals from Hall sensors are calculated by difference amplifier, then current feedback voltage u_fs) is outputted, making the drive a closed loop feedback system.

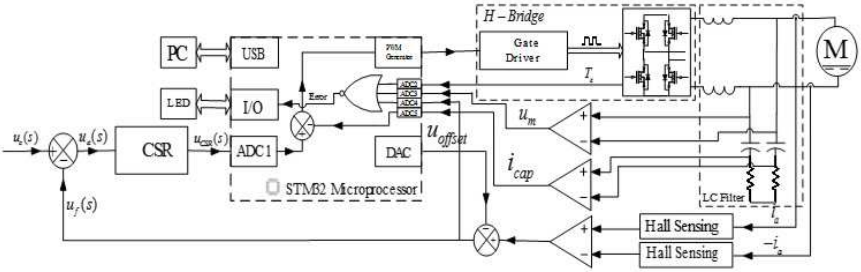

Figure 4: System diagram of motor drive

The zero-point bias voltage of Hall sensor is compensated by the analog signal u_{offset} from the digital-analog converting unit DAC of microcontroller STM32. Capacitance current of the LC filter is precision measured and sampled by ADC, the subtraction of which and $u_{CSR}(s)$ is used to improve the damping coefficient and to reduce second-order oscillation of the motor drive. There is also protection circuit in case of overvoltage, overcurrent and overheat.

3 Experiments

This paper develops an experimental prototype based on the design results, as shown in Figure 5. An air-cored Lorentz motor is built according to the design dimensions based on FE analysis results and the motor drive design. The driver module and the control module are developed as well. The experimental prototype also includes a test device to obtain the force constant and the dynamic response of the motor.

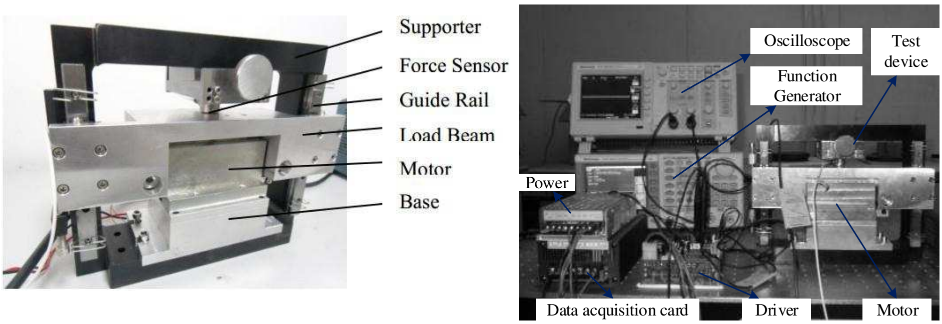

Figure 5: Experimental prototype

Test results are shown in Figure 6.The force constant of the designed motor is obtained as 72.16N/A (design target is 70N/A and the FE analysis result is 73.2N/A) with good linearity(the norm of residuals is 0.808). The following response of the motor force is fast (<0.5ms) within the working frequency (≤200Hz), and the force pulsation of the motor is low.

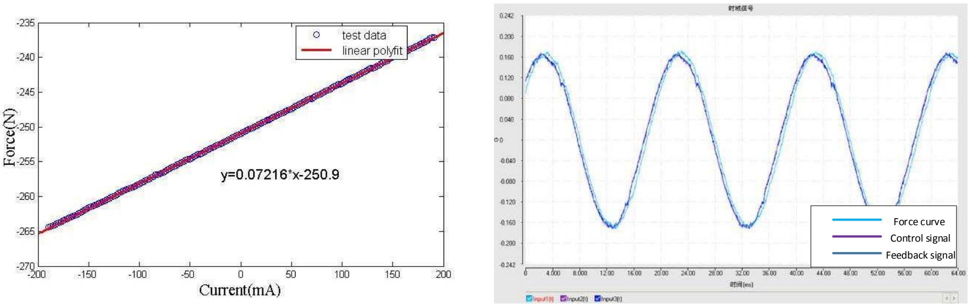

Figure 6: Force constant curve and dynamic response of the designed motor

4 Conclusion

This paper proposes a design method of Lorentz linear motor for active damping. An analytical layer model with proper simplifications is employed to quickly find preliminary optimal motor dimensions, and then the finite element (FE) model of the motor is built based on the analytical results. The analysis results of FE model help get further optimal motor dimensions. Then suitable controller is designed based on PII control algorithm. Finally, the performance of the motor is evaluated by experiments. The results of experiments show that the performance of the designed motor as the active damping component of a vibration isolation system is excellent. The proposed method is validated to be feasible.

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