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Proposal and analysis of three closed double magnetic circuits to obtain a very long stroke for electrodynamic force generators

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ABSTRACT

Electrodynamic force generators with a stroke of up to several hundred millimeters are in high demand in fields such as voice coil actuators and low frequency vibration metrology. The key is to extend the effective length of the long air gap (LAG) with required uniform magnetic flux density (MFD) and low magnetic flux leakage. This paper focuses on a proposal and comparative analysis of three closed double magnetic circuits (CDMCs) to obtain long/ultra-long strokes. Analyses are performed from the viewpoint of the magnetic line distribution, fringing effect, distribution of the MFD, and magnetic flux leakage in order to evaluate the stroke potential of three proposed CDMCs, while taking into account the vacuum annealing, material differences in permanent magnet pairs (PMs), and assembling errors in PM arrays. Analyses show that the CDMC with PMs assembled at the ends of the center yoke exhibits advantages over the other two schemes. An electrodynamic force generator with an air gap length of 200 mm is constructed with this structure. Experimental results reveal an MFD of up to 233.5 mT, MFD non-uniformity of 0.2% in the LAG, and magnetic flux leakage of 3 mT, which meet the strict requirements in low frequency vibration metrology.

1. Introduction

Electrodynamic force generators (EFGs) [1,2] are a class of actuators that generate actuation along a long air gap (LAG) based on Lorentz force proportional to the coil current intensity. EFGs with short stroke which are often called voice coil actuators (VCAs) have already been fully discussed, focusing on positioning and tracking accuracy, acceleration capability with low heat dissipation, and small volume [3]. They are widely used in precision motion applications like hard disk drives [4], active vibration isolation system [5], because of their advantages such as direct drive, absence of cogs or mechanical hysteresis, and low force and torque ripple [6]. The stroke of a VCA often varies from several to dozens of millimeters. Recently, VCAs with a long stroke of up to several hundred millimeters are in high demand in fields of ultra-precision engineering, such as IC manufacturing equipment. EFGs with long strokes are often called vibration exciters [7]. A new research focus in this field is the demand for vibration exciters with long/ultra-long stroke and extreme high acceleration waveform accuracy, arising from ultra-low frequency vibration calibration. Ultra-low frequency vibration metrology down to 0.1 Hz [8], and even 0.01 Hz, has been proposed and is becoming bottleneck technology in various fields such as earthquake forecasting, sea-wave monitoring and warning, mineral exploration, aerospace engineering, and precision machining and manufacturing [9]. An EFG with a stroke above 1 m needs to be constructed for 0.01 Hz vibration calibration. The acceleration waveform harmonic distortion in vibration calibration is required to be less than 1%.

During the construction of EFGs with long strokes, the distribution of the magnetic field density (MFD) in an LAG should be as uniform as possible so as to increase the positioning accuracy for VCAs and to decrease the acceleration harmonic distortion for vibration exciters. The MFD in an LAG should have enough intensity to provide a thrust force. Single magnetic circuits (SMCs) with one magnet as the magnetic source, which are usually adopted in traditional EFGs, such as VCAs [10] and high frequency vibration exciters [11,12], exhibit obvious shortcomings in achieving a long stroke. Their MFD distribution along an LAG deteriorates as the stroke length increases. Owing to the fringing effect of open magnetic circuits, magnetic flux leakage at the ends of SMCs is a significant problem.

High performance EFG design with long/ultra-long stroke is the key during development of an electrodynamic vibration exciter and know-how of several exciter manufactures in the world. A

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rectangular closed double magnetic circuit (CDMC) has been proposed with ceramic permanent magnets (PMs) attached to the inner sidewall of the outer yokes along the LAG [13]. The vibration exciters based on this structure are designed with stroke lengths ranging from 100 mm to 450 mm, and used as national primary vibration standards in PTB, CSIR, INMETRO, etc. [11,12,14]. Two types of cylindrical EFGs with a stroke length of up to 1 m have also been developed, one with axially magnetized cylindrical magnets assembled at the ends of the center yoke [15], and the other with axially magnetized ring magnets assembled at the ends of the outer yoke [16]. In both types of EFGs, AlNiCo magnets are used as the PMs to simplify the difficult assembly of large bulk permanent magnetic (PMs) because the magnetization can be completed after assembling. However, in these designs, the moving coil needs to be kept far from the magnets to prevent demagnetization from the coil's magnetic fields, and AlNiCo magnets may easily lose their permanent magnetization during assembly.

This paper takes the 0.01 Hz low frequency vibration metrology as the background, and focuses on a proposal and comparative analysis of three CDMCs in order to achieve a uniform and high MFD along an LAG that ranges from several hundred millimeters to more than 1 m. The capabilities of the three structures of CDMCs in obtaining a long stroke are evaluated from the viewpoint of magnetic line distribution, fringing effect, distribution of MFD, and magnetic flux leakage by using the finite element method (FEM) and considering important influencing factors such as materials and assembling errors. Finally, an EFG with a 200 mm stroke is constructed with the chosen scheme, and experiments are conducted to verify the theoretical analysis models and the conclusions and performance of the proposed scheme. This research provides guidelines during the research of long stroke VCAs, low frequency vibration metrology, etc.

2. Proposal of three CDMCs with long strokes

2.1. Structure and basic principle

Three CDMCs with the potential for increased stroke length are proposed, as shown in Fig. 1. In all three CDMCs, the thickness of the LAG is designed to be 15 mm to accommodate the thickness of moving coils carrying large driving currents and coil skeletons. The stroke of all the three CDMCs is expected to be extended from several hundred millimeters to more than 1 m.

CDMCs can be designed in either cylindrical or rectangular shapes. The cylindrical shape is often used in short stroke VCAs. It is not suitable for long stroke EFGs because it is difficult to assemble the center and outer yokes coaxially and guarantee assembling precision, and the assembly of large bulk PMs is also very difficult. Therefore, the rectangular shape is adopted in the three CDMCs.

Each CDMC consists of pairs of PMs, one center yoke, two outer yokes, two end yokes, and one engaging moving coil. The three structures (structures I, II, and III) are designed with different configurations for the PMs. In structure II, the PMs at the same end of outer yokes form a pair of PMs. The basic concept of a CDMC is that each pair of PM excites a set of closed magnetic flux loops through the center yoke, LAGs, outer yokes, and one end yoke. A uniform distribution of the magnetic flux is formed along the LAGs, and the direction of the magnetic flux lines is perpendicular to the moving coil. According to Ampere's law, an electromagnetic force is generated and acts on the moving coil when the coil carries a driving current.

The equation of the thrust force generated by the current carrying moving coil is given as

$$F = \int I d\vec{l} \times \vec{B} \quad (1)$$

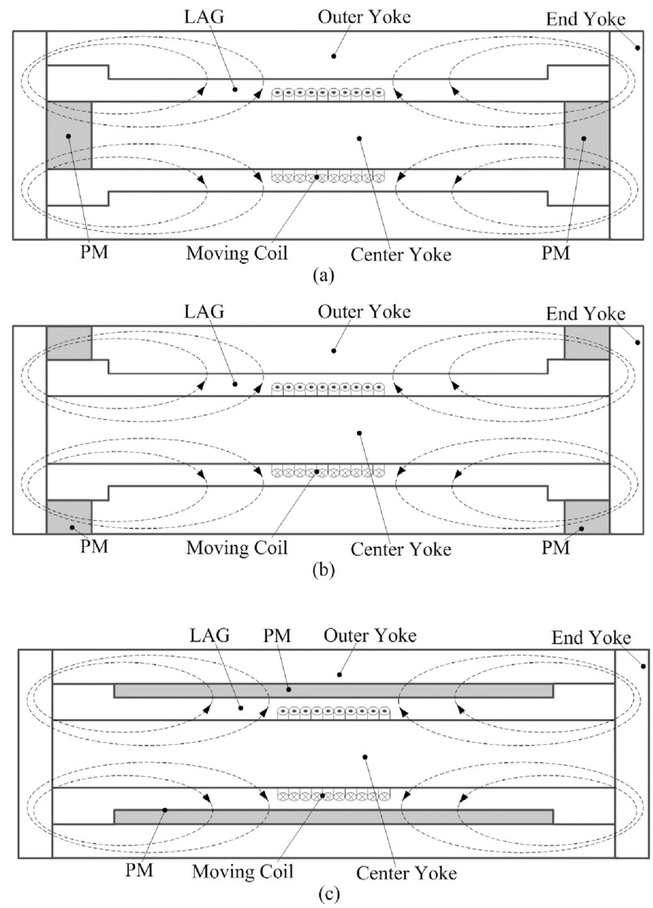

Fig. 1. Three rectangular CDMCs. (a) Structure I with PMs at the ends of the center yoke; (b) Structure II with PMs at the ends of the outer yokes; (c) Structure III with PMs attached on the inner sidewalls of the outer yokes.

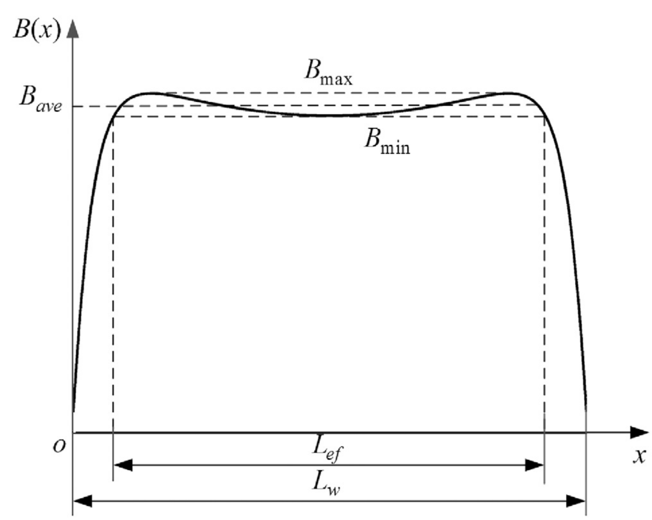

Fig. 2. Distribution of the MFD along the length of the LAG.

where F is the thrust force, I is the driving current, l is the length of the moving coil in the magnetic field, and B is the average value of the MFD in the LAG.

The fringing effect must be considered when calculating the distribution of the MFD along the LAG [17]. The shape of the MFD distribution looks like the alphabet "m", as shown in Fig. 2. L_w is the entire length of the LAG. The middle region of the MFD distribution along the LAG is a valley, and the minimum value of the MFD