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Frictionless Voice Coil Actuator: Design Review

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ABSTRACT

This paper studies frictionless voice coil actuators to deliver a large displacement stroke of ± 7.5 mm, producing peak force of 80 N. Voice coil actuators (VCA) work on Lorenz force and designed for nanometer level accuracy by various designers, for small displacement strokes in past. If VCA is supported with diaphragm flexure bearing, it gives frictionless, highly repeatable displacement and nanometer accuracy. In this paper VCA designs have been studied, and various geometries of flexure bearing have evaluated for desired output.

Keywords— **Diaphragm flexure, Lorenz force, Voice coil actuator.**

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I. INTRODUCTION

The voice coil actuator is a special form of a direct drive actuator with a similar working principle as the electric loudspeaker. The working principle is that in a magnetic field, the coil carrying current discharges power, the value of which is proportional to that of the coil current. The voice coil actuator has a structure of the moving coil type permanent magnet linear actuator, mainly composed of the stator and the rotator. The stator includes a magnetic yoke and a double-bar permanent magnet of symmetrical layout, while the rotator is composed of the coil winding and the winding bracket.

There are many different methods of producing controlled linear motion, or linear positioning [1]. Conventional means include air cylinders, ball screws, cables and pulleys, or even stacks of piezoelectric elements, but probably the most common is a stepping motor in which the shaft is replaced by a screw.

II. VOICE COIL ACTUATORS

Linear voice coil actuators (VCA) come in two forms—moving coil and moving magnet types. Unlike solenoids, in voice coils a reasonably uniform magnetic field is generated across a fixed gap using a powerful permanent magnet. The coil lies within this space and is held in neutral position by a spring mechanism. Linear VCA range from the small, with peak forces from 0.7 N and strokes of 1 mm, to large with forces of 2000 N and strokes of up to 50 mm.

VCA for robots which are made for human interaction purpose are preferred for their controllability, ease of implementation, geometry, compliances, safety, quietness, and high power density [2]. They have peak forces approximately 11 times greater than their weights, making them suitable for various applications.

A. Design Considerations

When a current carrying conductor is placed in a magnetic field, a force is produced in a direction perpendicular to both the direction of the current and the magnetic field. This is the Lorentz force law and can be stated as

$$F = I \times L \times B$$

where F(N) is the force vector of conductor, I (A) is the current vector, L(m) is coil length and B (weber/m^2) is the magnetic vector or flux density.If conductor is wound into coil i.e. solenoid of length L(m),

$$B = \mu \frac{NI}{L}$$

where N is number of turns, μ(weber/A-m^2) is permeability of metal (usually iron). A double bar permanent magnet with symmetric layout helps to operate entire air core coil within magnetic field region. R. Liu [3] suggests Voice coil design and permanent magnet selection for VCA.

TABLE I
MAGNETIC PROPERTIES OF PERMANANT MAGNETS [3]

Material	B_r (T)	H_c(kA/m)	$B{*}H_{max}$(kJ/m^3)
AlNiCo	1.230	51	44
MnAlN	0.560	239	61
$SmCo_5$	0.870	637	146
NdFeB	1.230	881	290

Table shows that, NdFeB is the most suitable material, for VCA, as it gives high magnetic residual induction intensity B_r, high correctivity of magnetic flux H_c, and maximum energy product B*H. Considering VCA size and the manufacturing cost, NdFeB is selected as actuator base material.

III. DIAPHRAGM FLEXURES

Diaphragm flexures are commonly used to provide precise out-of-plane motions in various applications such as voice-coil actuators, pressure sensors, flow control, flexible couplings, MEMS devices, and frictionless linear bearings.

Various geometries of diaphragm flexures have proposed, and studied by researchers for linear compressors.

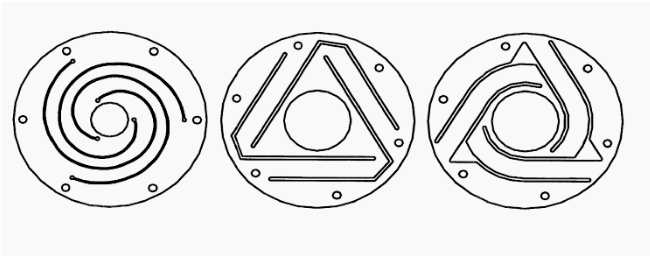

Fig. 1 Diaphragm flexure geometries [12]

Gaunekar et.al [4] and Malpani et.al [5] presented Finite Element Analysis (FEA) approach for circular flexure with three spiral cuts. For triangular, rectangular, elliptical and square shaped diaphragm flexures used in linear compressors FEA is found to be suitable [6].

A typical planer diaphragm flexure, comprising of an inner diaphragm, an outer frame, and intermediate flexure support units, offers three out-of-plane Degrees of Freedom (DOF) and three in-plane Degrees of Constraint (DOC). Awtar et.al [7] have proposed design of symmetric diaphragm flexure, as shown in fig. 2, which offers an optimal overall performance, and used as basic building block in the construction of other flexure systems such as torsion couplings, MDOF stages, linear bearings, linear drive reciprocating compressors. Awtar et.al [8] presented closed form analysis of simple curved beam, and derived force- displacement characteristics of beam using Euler Bernoulli approximation. In derivation nonlinear elastokinematic terms arising due to force-equilibrium in deformed state are not considered.

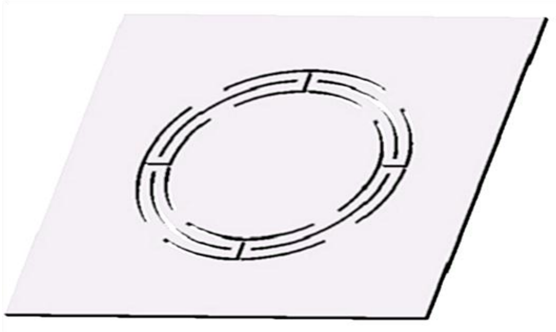

Fig. 2 Optimal Symmetric Diaphragm Flexure [7]

Teo et.al [9] proposed semi analytical approximation model for analysing large nonlinear deflection of beam-based flexure joint, as shown in fig. 3. Also they present a nanopositioning actuator with stroke range of ±1 mm with positioning stability of ±10 nm, and studied thermal stability with the help of lumped parameter modelling approach of Lorentz force Electromagnetic Driving Module (EDM) [10].

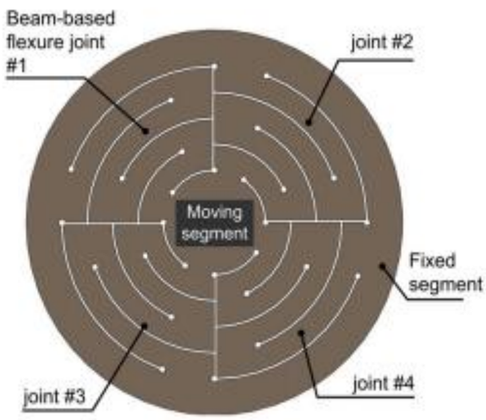

Fig.3 Flexure with four beam based flexure joints [10]

Jomde et.al [11] studied variation of stiffness in diaphragm flexure bearing, due to change in number of spiral arms, disk thickness and spiral angle. The study is useful in designing VCA with large stroke upto ±7.5 mm and delivering desired force output of 80N, which is the intension of this paper.

IV. DESIGN CALCULATIONS

Frictionless VCA design consists of Voice coil, Permanant magnet and Diaphragm flexure design separately. Past researchers have used analytical method to design VCA, and achieved considerably small stroke lengths. For diaphragm flexure design FEA is the most suitable method for the nonlinear force displacement behaviour.

A. Voice Coil Design

As per design requirement the motor thrust F= 80N,

$$\frac{V}{R} = I$$

$$R = \frac{\rho L}{A}$$

Where is resistivity of wire (for Copper =1.78*10^{-8}).

If effective coil length is taken equal to the actual length and voltage= 12 V, air gap flux density = 0.65 then by calculations,

$$F = {}^{B_g V A}/_{\rho}$$

Cross sectional area of copper wire comes to be 0.178*10^{-6} m^2 , and diameter 0.472 mm. According to enamelled copper wire specifications, we can choose 0.470 mm wire with max insulated diameter 0.510 mm. We have to take 8 layers of enamelled wire, with 150 turns in each layer i.e. 2000 turns.

The coil wire length is given by

$$L = \frac{F}{IB_g} = \frac{80}{1 * 0.65} = 123.07m$$

The wire resistance comes out to be 12.33 Ω. Current I≈ 1 Ampere. Corresponding electromagnetic thrust

$F = I \times L \times B$ = 79.95 N.

B. Magnet Design

Permanent magnet NdFeB is to be taken as magnetic material as if gives maximum energy product. The electromagnetic FEA is helpful in calculating size of magnet, since dimensional constraints are to be considered.

C. Diaphragm Flexure Design

All available shapes of diaphragm flexures should be studied, with change in geometry, effective arm configurations, different materials, change in thickness. The required stroke length demands for low stiffness in axial direction, and max. stiffness in all other directions.

V. CONCLUSION

Scope of this paper was to review past designs of Frictionless VCA, and proposing method of design for desired stroke length, and force output. In further work we are going to work on FEA & Electomagnetic FEA of various possible configurations to optimize the actuator design.

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