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Review of Moving Magnet Linear Oscillating Actuator for Linear Compressor Application

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Abstract

This paper overviews the recent developments and new topologies of single-phase moving magnet linear oscillating actuators (MMLOA). The key advantage of the MMLOA when compared with conventional LOA is the absence of screws, gears, and crankshaft mechanism which results in fewer mechanical parts, simple structure, easy fabrication, lower noise levels, and negligible frictional losses. The structural designs of alternative topologies are deliberated in detail and their relative merits, as well as demerits, are evaluated. Specific design issues, including pole and tooth number combinations, stroke length, magnet pole ratio, and split ratio are investigated. The imperative phenomenons of the resonance as well as the adjustable stroke are also discussed in detail. MMLOA type linear compressors are superior over other conventional compressors accommodating actuators with rotary to linear mechanisms for significantly higher efficiency, high thrust density, lower losses, fast responses, and smaller time constants. Finally, the electromagnetic performance in terms of thrust force of selected MMLOA topologies is also compared with other state of art proposed designs.

Keywords: Electromagnetic force, linear actuator, Permanent magnet, reciprocating motion

Introduction

There are some applications that required linear reciprocating motion, like refrigerant pumps and compressors [1-3]. Owing to high consumption and lack of availability of energy supply, the emphasis is currently on saving energy from household appliances, especially refrigerators that consume 20 to 40 percent of house's electrical energy. An outsized amount of energy is consumed by the compressors within the refrigerators. A high performance compressor will save a significant amount of energy [4-13]. A piston in conventional reciprocating pumps or compressors typically involves both rotary as well as linear motions. Mechanical failure may occur by this method which involves linear motion mechanism from a rotary motor to the crank-shaft [9]. That's why the conventional linear compressor has small efficiency of the system [1]. The primary linear compressor prototype was introduced as a replacement in 1994 [13]. High dynamic performance, rapid response, and high reliability are the major characteristics that distinguish this linear reciprocating actuator from conventional one due to the absence of mechanical energy conversion system [14]. Due to no end winding effect, maximum utilization of PM and high air gap flux density compact structure tubular shaped LOA are most preferred compare to flat shape [15].

There might be three configurations based on a design of linear actuator. In the first configuration, both stator and the mover have coils (moving coil), so that the field is generated electromagnetically by both parts, second configuration has PMs placed on the mover while coils wounded on the stator (moving magnet), and in the third configuration, coil is housed in the stator while the mover is just composed of iron rod (moving iron). The other types of LOA are lower in ranking than moving magnet type due to low inertia, high thrust force density, rapid response, and loss of energy [16]. Moving magnet linear actuator has different permanent magnet configurations housed on the mover as depicted in Fig. 1. Radially magnetized PMs, as they are only available in arc shape, have the limitation of low mechanical strength. Moreover, the magnetic flux distribution of radially magnetized PMs is not perfectly ideal, due to which thrust force response is low. Halbach array configuration is used in [17-21]. Which consists of both radially and axially magnetized PMs, but it increases the cost of the LOA and decreases the mover's mechanical strength. Tubular radially magnetized PMs are not easy to magnetize as compared to disk or bar-shaped axially magnetized PMs. In addition, radially magnetized PMs have a higher cost of PMs and fabrication than axially magnetized PMs.

In the design of LOA, mechanical resonance is the most important parameter. Total energy consumed by the system is minimized by LOA with spring assisted assembly. The basic principle of installing spring in the LOA system is to store and discharge energy, whenever needed, from and into the system [22].

Stroke of the LOA can be regulated by adjusting the frequency and amplitude of the input AC. LOA performs efficient operation when frequency of the mechanical system becomes equal to the operating frequency of the electrical system [21-24].

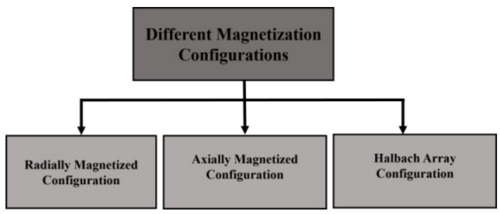


Figure1: Different magnetization configurations

This paper summarizes the recent development and new topologies of MMLOA. The paper is structured as follows. The operating principle of MMLOA is briefly described in section 2. Alternative MMLOA architecture topologies are reviewed and their novel features are demonstrated in section 3, while section 4 addresses design issues. The imperative phenomena of the resonance as well as the adjustable stroke are discussed in section 5 and section 6, respectively. Finally, in section 7, selected MMLOAs are equated with other state-of-art designs proposed in terms of the thrust force.

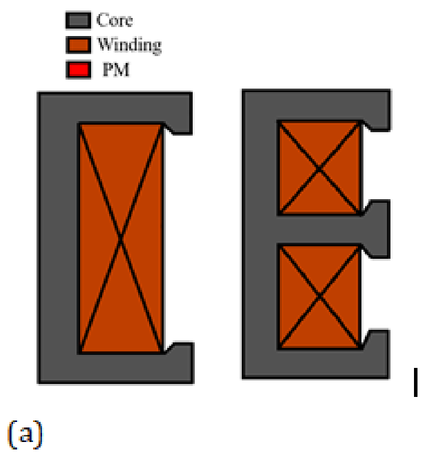
Operating Principle of Linear Actuators

There are two fundamental principles that are followed by the linear oscillating actuators. The first one is the principle of electromagnetic actuation in which the stator magnetic field makes the iron translator shift to the place where the magnetic field lines are facing the least reluctance path. The second one is the principle of electrodynamic actuation in which the magnetic field generated by one part intermingles with the other using Ampere's law. As discussed earlier there are three types of LOA configurations. In moving-coil configuration, magnetic field produced by the coil of the stator interacts with field of the coil, housed on a mover. Similarly, in moving magnet configuration, field of stator coil interact with PMs field fixed on a mover. Moving solenoid uses principle of electromagnetic actuation where magnetic flux lines align themselves to pass through least reluctance path. Mover adjusts their position to provide the least reluctance path to the magnetic flux and undergo a unidirectional force [16].

Alternative Actuator Topologies

All the MMLOA topologies that have been developed, some of them are under working and are outlined as follow

- E-core SPM LOA
- E-core IPM LOA
- E-core HSPM LOA
- C-core SPM LOA
- C-core IPM LOA
- C-core HSPM LOA



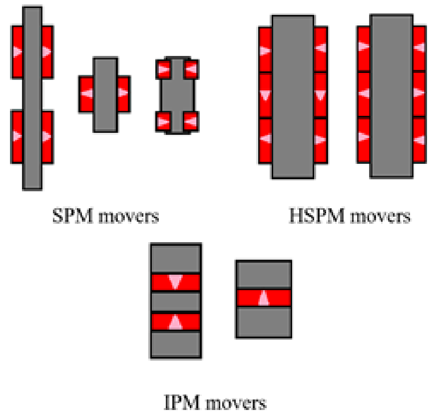


Figure2: Different stator core and mover topologies: (a) C-shaped stator core and E-shaped stator core cross section (b) SPM, HSPM and IPM type mover

Fig. 2 shows the different topologies for stator core and the different topologies for mover as well [25]. For both single phase C-core and E-core tubular MMLOAs, alternative design topologies are proposed in [26-32]. Besides, comparison of radially magnetized SPM LOA with E-core 2-pole tubular LOA fortified with HSPM is taken into the account and considerable improvement in performance is claimed.

Single-phase alternative C-core actuator topologies based on [26] are designed and analyzed in [33] by FEA, as well as an E-core IPM LOA. Cross-sectional view of the E-core IPM LOA is presented in Fig. 3, which consists of two circular windings accommodated by an E-shaped ferromagnetic stator core and a mover, in which ferromagnetic iron block is placed at both sides of axially magnetized PM ring. An almost similar structure of stator in this E-core IPM LOA is used compared to the HSPM LOA mentioned in [32] also depicted in Fig. 3. The superiority of C-core LOA over E-core is its ease of manufacture, while flux leakage of E-core stator is lower than C-core stator. Furthermore, for the same LOA size, the coil used in the C-core is bulkier than the E-core, increasing the risk of coil overheating. As a result, the E-core LOA outperforms the C- core LOA. Stiffness coefficient can be improved because of reluctance force produced by the E-core IPM LOA due to saliency in mover structure which is favorable to the oscillation. Meanwhile, with half the use of PM material, it is capable of generating the same peak force as the HSPM actuator whereas the mover structure is much simpler and easier to build. However, the E-core type stators possess an extensive downside of limited slot area which increases the difficulty of inserting winding during fabrication. A special lamination stacking method is used to make stator cores in both C- and E-core type LOAs e.g. SMC or some special material is used which is not that easy to make. Therefore, a TF LOA has been proposed in [33-36] to overwhelm the drawback of radial magnetic field creation. This topology possessed same stator construction as used in standard rotary motor, and is not hard to fabricate.

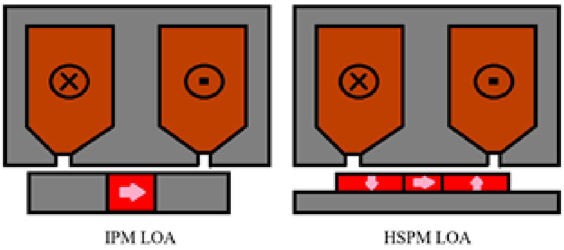


Figure3: Cross-sections of E-core IPM and HSPM LOAs

While using a TF configuration in [35], a comparison between moving magnet LOA and moving magnet plus moving iron core LOA was taken into the account and concluded that armature thrust force of TF LOA is directly proportional to the current passes through the coil. Moreover, both TF LOAs have same thrust force, but the moving magnet TF LOA has an inferior thrust force density while greater resonant frequency [26-36]. So the former TF LOA type is relatively easy to construct and has a great scope in future. A single-phase TM LOA design was suggested in [37, 38]. Two outer stators carrying concentrated armature winding and an inner stator composed the static assembly of this TM LOA topology. Inner and outer stators are placed around the mover. Parallel magnetization is done on six PMs having alternating polarity. These PMs are mounted uniformly on a non-ferromagnetic support tube. Cross-section of the TM LOA is illustrated in Fig. 4. It should be noted that the total mover displacement must be less than the length of outer stators. To place the end winding, the gap between the two stators should be sufficiently long. The maximum stroke is obtained if the summation of lout and li is equal to the PMs axial length. The design goal should be to ensure both the stroke length and low cost while assessing the axial length of the PMs. High thrust force density as well as outstanding dynamic performance is achieved using this topology. In addition, it prevents the limitations of challenges faced in manufacturing process and low permeability. As TM LOA has a complex fabrication that requires more mechanical parts. This topology is restricted to 3D-FEA only, as its mover displacement and the flux paths include the circumferential direction, radial direction, and axial direction that take more computational time.

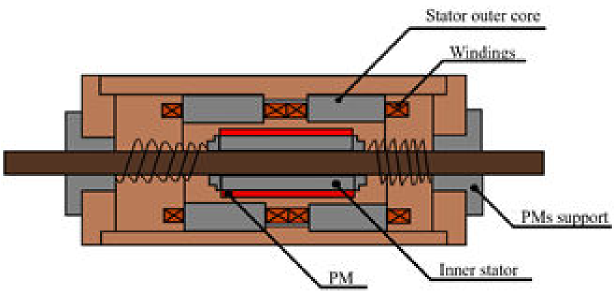


Figure4: Cross section of transverse flux moving magnet linear oscillating actuator

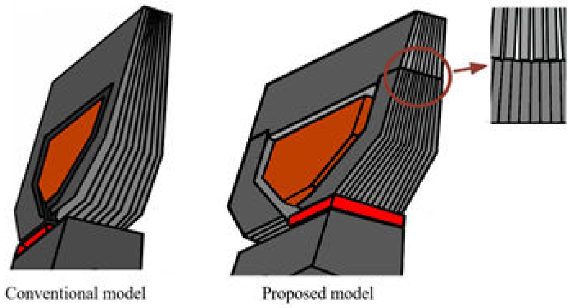


Figure 5: Radial lamination of conventional model and proposed new model of LOA

Normally, stator core is laminated towards the central axis to minimize the eddy current losses in typical rotary machines. But in case of LOA, it must be laminated radially because lamination toward axis is not possible. While using the conventional radial lamination, air gap has a low flux density due to small stacking factor. To overcome this problem, a new radial lamination method is suggested in [39] that laminates a separate formation of the stator teeth and stator yoke. Ferrite PM is used to design this LOA because the neodymium PM is expensive in cost and its stable supply cannot be assured. The proposed technique multiplies the air gap flux density due to enlarge stacking factor as compared to existing technique. Comparison is carried out between both models in terms of back emf and thrust force. The conventional radially laminated design is shown in Fig. 5 with a small stacking factor, resulting in decreased output power according to the reduction in air gap flux density. Fig. 5 also shows the new lamination model that has a greater stacking factor by laminating the teeth and yoke separately. It will provide great output power because the increase in stacking factor increases the air gap flux density. Eventually, the effect of fabrication error is detected in proposed model and it is confirmed that the fabrication error does not have a significant impact on the power of machine.

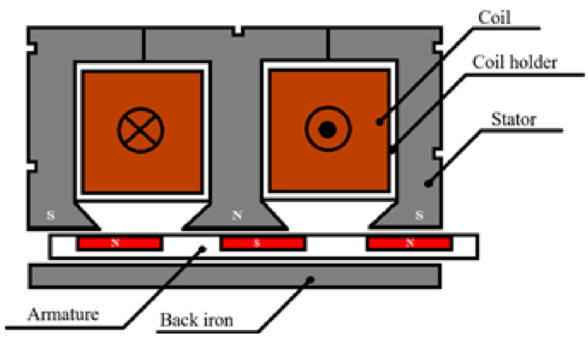


Figure 6: Cross-section schematic of MMLOA

A new design of a single-phase tubular moving magnet linear actuator suggested in [40-42]. It consists of armature that has

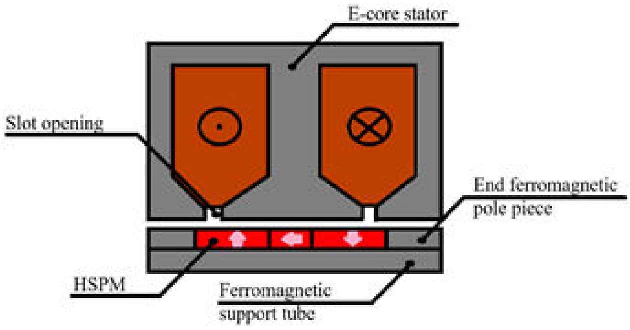


Figure7: Structure of EF-HSPM LOA

The performance of tubular LOA is improved by using ferromagnetic pole pieces in [15]. At both ends of the supporting tube, ferromagnetic pole pieces are employed constructing a salient mover structure. This saliency in mover structure decreased the air gap reluctance at the ends due to which the flux density of the effective air gap is enhanced. A tubular HSPM configuration is used in this design, as shown in Fig. 7. This HSPM LOA with end ferromagnetic pole pieces is compared to the proposed HSPM LOA in [27, 44, 45]. The results demonstrate that this EF-HSPM LOA design is more preferable to the initial HSPM LOA. Improvement in the flux density of the air gap boosted the electromagnetic performance of HSPM LOA. But the main downside of this design is the bulkier mover mass because of the placement of ferromagnetic pole pieces.

Rare-earth PMs are commonly used for short-stroke LOAs. However, these PMs are costly and are influenced by the unreliable material supply. A ferrite PM LOA was therefore proposed in [46] to substitute the rare-earth PM LOAs. For comparison, both models rare-earth PM LOA and ferrite PM LOA are designed, shown in Fig. 8. Rare earth PM LOA construction involves moving PMs, stator cores, and coils. These moving PMs are radially magnetized but mover moves in axial direction. The ferrite PM LOA is also composed of a moving part, stator cores, and coils. The ferrite PM with the core constitutes the moving part. The EMF is generated when the moving part oscillates back and forth on the z-axis, analogous to the rare-earth PM LOA. The outer PMs that are embedded in the outer stator are magnetized axially. Ferrite PMs have poor demagnetization features so while designing they are kept thicker relative to the rare-earth PMs. In order to reduce core losses, both versions are laminated radially. Conventional ferrite PM LOAs have massive mover that make it inappropriate for high speed task. In this topology the ferrite PM LOA is modeled with light mover mass containing PMs and iron core. Tuning capacitors are used to overcome the high inductance of ferrite PM LOA. The ferrite PM LOA and rare-earth PM LOA have similar performances. The main limitation of using ferrite PM is heavier mover mass as compared to rare-earth PM mover mass due to this more current is drawn, which in turn would increase the copper losses.

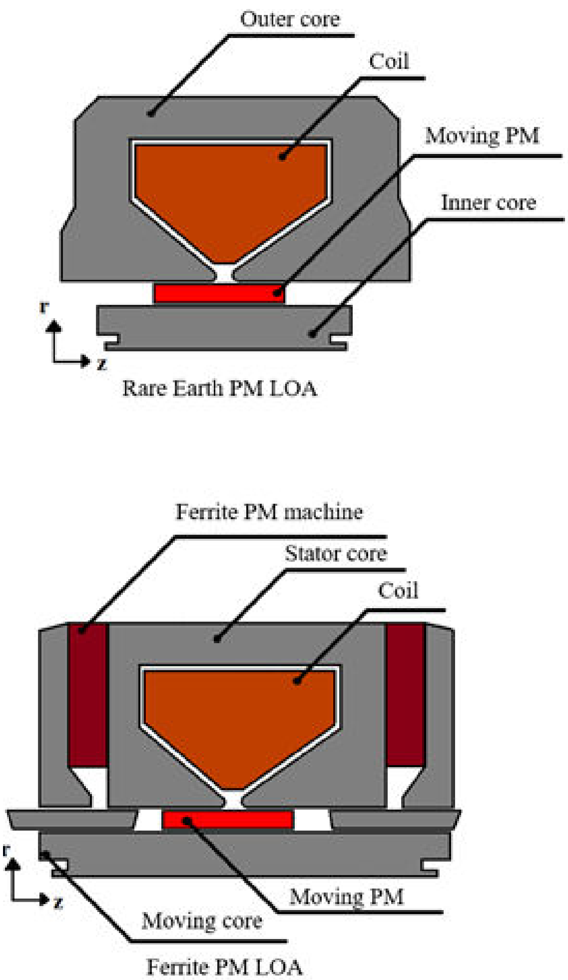


Figure 8: Structure of rare-earth PM LOA and ferrite PM LOA

IPM LOA provides greater power density than usual LOAs, but significant side forces are produced by this configuration. The actuator may fail to function properly due to the eccentricity of the electromagnetic behavior. Therefore, a new design is developed in [47] to reduce the effect of side forces. Fig. 9 displays the IPM LOA structure consisting of coils, moving cores and segmented stator cores. Moreover, the axially magnetized PMs are embedded in the mover, which reciprocates along the z-axis. To overcome the defect of strong side forces, electromagnetic design is formulated. The electromagnetic side force denoted by fs is calculated using (2):

$$f_s = \frac{S}{2\mu_o}(B_r \times B_z) \quad (2)$$

By reducing the utilization of PM material or by increasing the magnetic air gap, the side forces can be reduced. The method used in this proposed configuration also shown in Fig. 9 is the insertion of bridge in the PMs to minimize the amount of PM material that somehow leads to degradation of the IPM LOA performance. Therefore, the optimization is performed for the position of the bridge in the PMs. After optimization, however, there is still a drawback that the output thrust force has also decreased with the minimization of the side forces.

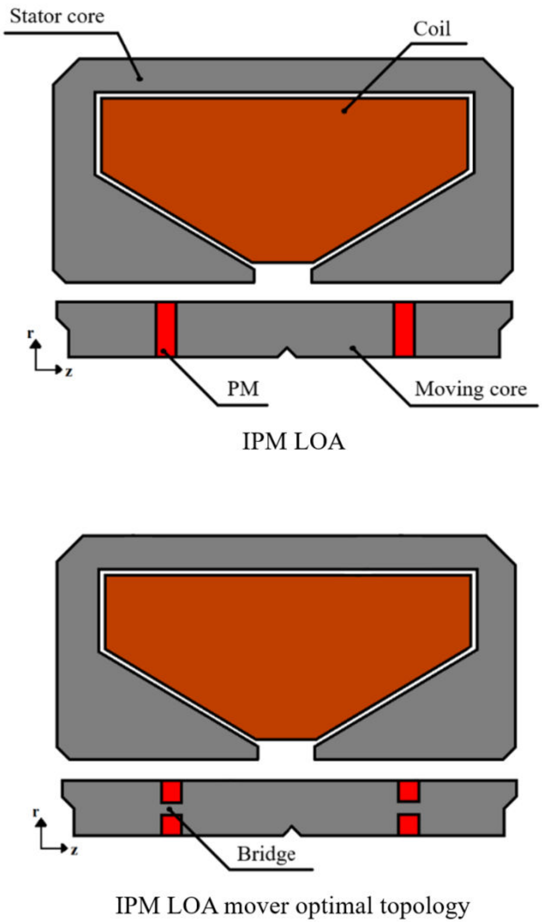


Figure 9: Structure of IPM LOA Cross-section and IPM LOA mover optimal topology

While designing the LOA magnetic flux density generation, fabrication as well as cost can be greatly influenced by shapes of the PM. Generally, axially magnetized PMs are available in discs or cylinder geometry while the radial magnetized PMs exist in arc shapes to mount on the moving part. Since the axially magnetized PMs can be easily embedded on the mover as compared to radially magnetized PMs [48]. Arc shaped magnets make the moving assembly feebler as compared to the disc or cylindrical shaped magnets. Additionally, the thrust force of the LOA is effected by the poor magnetization of the arc magnets relative to the axial magnets. Moreover, the axially magnetized PMs are cheaper in cost than the radially magnetized PMs. By taking these facts into the account, an axially magnetized MMLOA was proposed in [49]. Fig. 10 shows the cross-sectional view of the axisymmetric topology of LOA. The stator and the mover are the two primary parts of this LOA design. The stator is composed of C-core that encapsulates the winding woven around the central axis. 2D axisymmetric cross-section of this proposed LOA is shown in Fig. 10. The C-core sides are referred to as legs of the stator. Pole shoes are manufactured at each leg of the stator because sharp edges give greater reluctance to the magnetic field lines. Mover of this design is composed of three parts; flux bridge, core materials and PMs. Two axially magnetized disc-shaped PMs are mounted on either side of the mover core. The flux bridge is designed in order to provide the return path for the magnetic flux lines coming from mover back to the stator, which is connected behind the mover. The mover core is a hollow tube which is sandwiched between the two PMs for flux transmission. Consequently, the mover weight is reduced by using low carbon steel as a fabric of the mover core and by making bore with optimum dimensions, but the mover mass has been increased by the use of the flux bridge. This LOA design with low fabrication cost and inexpensive PMs, produces high thrust force in the viable stroke region. However, this topology has intricate fabrication owing to its complex structure. Additionally, the moving mass of this LOA design is higher than [40, 50] which is the constraint of this LOA. By using axially magnetized ring-shaped PMs, this restriction can be eradicated, but it will however be more costly

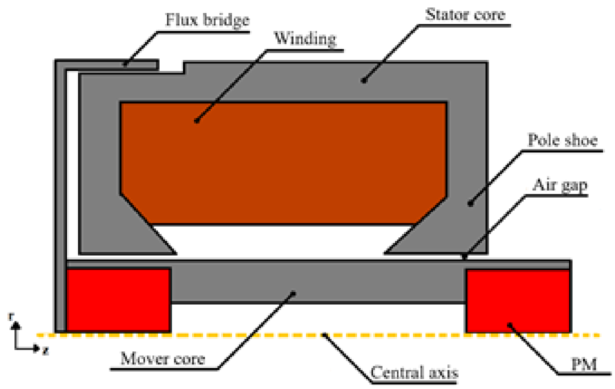


Figure 10: Cross-section of 2D-axisymmetric topology of LOA

Design Issues

The electromagnetic performance of the moving magnet linear actuators relies on many design parameters. These key design parameters are summarized as follow:

Pole and tooth number combinations

All the C-core and E-core type MMLOAs have a common trait that the mover pole number and the stator tooth number vary by one [51].

$$|N_t - N_p| = 1 \quad (3)$$

Using expression (3) all the possible combinations of and are calculated in Table 1.

Table 1: Possible Pole and Tooth Number Combinations

Nt	Np
2	1,3
3	2,4
4	3,5
…	…

Stroke length

LOA converts electrical energy to the mechanical energy using me chanism called electromagnetic force. The mover's working stroke is usually less than one pole pitch to ensure a consistent direction of the output thrust force [51].

Number of turns

For designing C-core and E-core stator types, the number of turns can be calculated using (4):

$$N = \left(\frac{C_W}{C_D} \times \frac{C_H}{C_D}\right) \times F_f \qquad (4)$$

Magnet pole ratio

The magnet pole ratio is defined as

$$\alpha_p = \frac{\tau_{Fe}}{\tau_{Fe} + \tau_{pm}} \qquad (5)$$

Has a major influence on LOA performance. Hence, the optimal pole-ratio is required to achieve the maximum thrust force, either by finite element analysis or analytical modeling, while retaining the other parameters fixed [51].

Split ratio

Split ratio is defined as the ratio of stator bore radius () to stator outer radius ():

$$\alpha_s = \frac{R_s}{R_o} \qquad (6)$$

It is a significant design parameter for tubular PM machines, as it has a substantial effect on the thrust force competency, performance, and the cost as well [45].

Resonance Operation

LOA normally works under resonance condition that distinguishes the performance of the LOA to a great extent, compared to conventional actuation method. At resonance operation, minimum input current is required for feasible operation of the LOA [48]. However, stroke of the LOA will be smaller compared to other operating frequencies owing to smaller amount of the current through coil. Due to smaller amount of current, electromagnetic force of the LOA will be smaller at resonance operation. Stroke to current ratio as well as stroke to electromagnetic force ratio of the LOA will be high at resonance frequency of the operating LOA. Moreover, efficiency of the actuator will be high on account of smaller input current at resonance, which will further lead to low ohmic losses [12, 50] and makes the coil harmless. Furthermore, mechanical and electrical impedance of the LOA, will have minimum influence at resonance frequency.

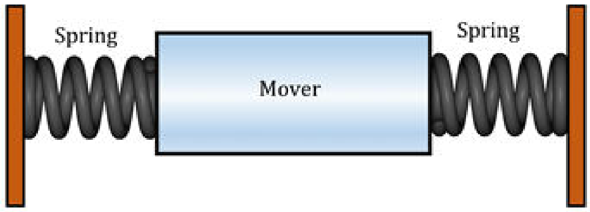


Figure 11: Schematic diagram of mass spring system of LOA

There are two types of resonance phenomena that can be accomplished in LOA: mechanical resonance and electrical resonance. Mechanical resonance is attained by operating LOA at mechanical resonance frequency. Mechanical resonance is based on mover mass and spring stiffness. Expression for mechanical resonance frequency is

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (7)$$

Where is the mechanical resonance frequency, is the stiffness of the spring and m is the mover mass. The general representation of mass spring system of LOA is shown in Fig. 11. Springs attached to the mover absorb and release energy from the mover when required for free oscillations Mechanical springs used in conventional designs face some issues like friction, material failure and fatigue. To overcome these issues, magnetic springs as alternative to mechanical springs are used discussed in [22]. Magnetic spring is the best substitute for mechanical spring in case of high frequency oscillation, long stroke and compact design.

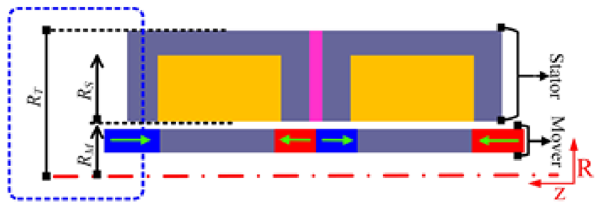


Figure 12: General topology of LOA

In terms of resonant frequency, moving mass plays a vital role in LOA design. The higher the value of the operating frequency, the LOA produces more output power. Design with high resonant frequency is more preferable in future. Reduction of the mover mass greatly affects the resonant frequency since it can be varied within a specific range, due to design constrained [50]. Split ratio has a great impact on efficiency, thrust force and mover mass of the LOA. A technique is proposed for the future work on the basis of split ratio. The proposed technique is applied to the topology shown in Fig. 12. In this procedure, is kept constant while mover radius is kept variable. Moreover, is also constantly changing. Fig. 13 illustrates the effect of split ratio on thrust force, mover mass and operating resonance frequency. By increasing, thrust force increases up to optimum value of the split ratio. The mover mass increases and the operating resonance frequency decreases during this procedure, keeping the constant value of the spring stiffness.

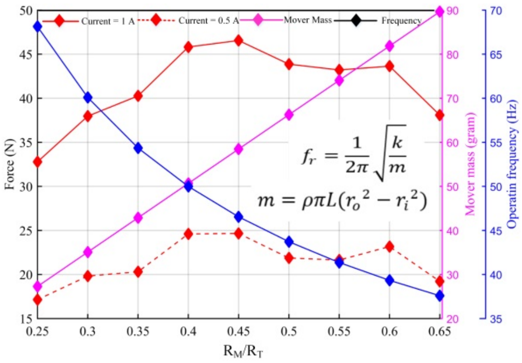


Figure13: Proposed mover mass reduction technique

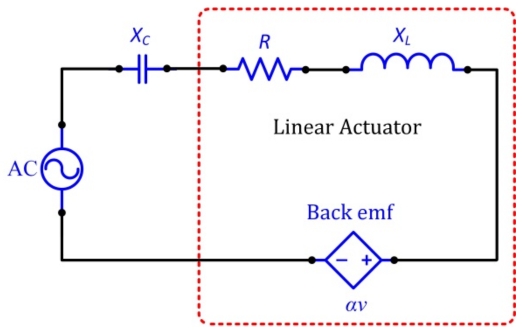


Figure 14: Equivalent electrical circuit of LOA

Beyond the optimum value of the split ratio, there is a significant decrease in the value of thrust force and the value of mover mass increases proportionally. The resonant value decreases due to an increase in the value of the mover mass. Hence it is concluded that mover mass should be selected on the basis of optimum value of the split ratio.

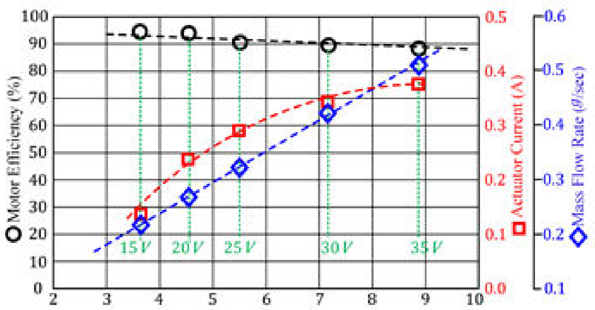


Figure 15: Efficiency and mass flow rate for various values of input voltage and current

Another characteristically gain of LOA, is the creation of electrical resonance, during the LOA operation. Electrical equivalent circuit of LOA is generally composed of resistance and inductance as shown in Fig. 14. Back emf; the product of back emf constant and mover velocity, represented by and, respectively [50]. An external capacitance is used to make the effect of inductive reactance negligible. Inductive reactance is canceled out by capacitive reactance by exciting the LOA through an excitation source with a frequency equal to the electrical resonance frequency. At this condition, the whole load of the LOA will act as a resistive load, thereby reducing the loss of input power. Expression for the value of capacitance required is

$$C = \frac{1}{4\pi^2 r^2 f_r^2 L} \quad (8)$$

Where the required capacitance for creating electrical resonance is is the operating resonance frequency and is the inductance of the coil [49]. From (8), it is also obvious that for higher value of the operating frequency, less capacitance will be required to create electrical resonance.

Adjustable Stroke

LOA operates at a variable range of the stroke compare to the conventional actuation method. Increasing the range of the stroke increases the compressor's cooling power and mass flow rate. The LOA stroke can be adjusted by input loading to the LOA. However, to get a high stroke of the LOA, required input power to the LOA should be high [40]. High input power reduces the efficiency of the LOA due to more copper losses. The relation of stroke with power consumption and cooling capacity is investigated in [51], which clearly reveals that higher stroke of the LOA can be achieved if the power consumption by the LOA also increases. Moreover, it is obvious that by increasing the stroke of the LOA, more compression of the gas is accomplished, which further contributes to an improvement of the compressor's cooling capacity. However, for high power consumption, input voltage of the LOA will be high and hence more current will pass through the coil. Fig. 15 shows actuator efficiency for different values of the applied voltages analyzed in [40]. By increasing coil voltage, stroke of the LOA increases, which leads to increase the current through the coil. At higher value of the current, efficiency of the LOA reduces, due to increase in copper losses.

Comparison of Thrust Force

Some important specifications of different MMLOA are illustrated in Table 2 in which four major parameters are chosen to differentiate MMLOAs from one another. From the Table 2, it is obvious that the MMLOA with flux bridge topology has the highest thrust force because of the large volume of the PMs used which consequently increased the mover mass but based on overall performance analysis, single-phase EF-HSPM LOA has the highest efficiency.

Table 2: Mmloa Comparison

Ref.	Tubular Topologies	Mover Mass (kg)	Max Stroke (mm)	Thrust Force (N)	Efficiency (%)
(Lu et. al, 2015)	TMLOA	0.7	10	144	Not mentioned
(Hassan et. al, 2016)	MMLOA with radially magnetized PMs	0.68	8.8	75	73

(Sun et. al, 2018)	HSPM LOA EF-HSPM LOA	0.478 0.518	14 14	78.20 99.02	90.49 92.48
(Kim et. al, 2019)	MMLOA with Rare Earth PM MMLOA with ferrite PM	0.52 2.70	12 15	139 190	87.5 90.7
(Kim et. al, 2020)	IPM LOA	0.4	15.1	63	92
(Ahmad et. al, 2020)	MMLOA with flux bridge	1	14	365	89.9

Conclusion

In this paper, an overview of recent development and novel MMLOA topologies in terms of their design has been presented. The merits and demerits of these design topologies are qualitatively discussed. Specific design issues, including pole and tooth number combinations, stroke length, magnet pole ratio and split ratio. The two most significant phenomena the resonance operation and the adjustable stroke are addressed. At resonance, minimum input current is required for feasible operation of the LOA. Efficiency of the actuator will be high on account of smaller input current due to decrement in ohmic losses. The thrust force of some selected topologies is also compared. So it is concluded that the MMLOA with flux bridge topology has the highest thrust force because of the large volume of the PMs used which consequently increased the mass of the mover but based on overall performance analysis, single-phase EF-HSPM LOA has the highest efficiency.

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