

Effect of Cogging Force on Linear Haptic Motor

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Abstract. As consumer electronics evolve, precise tactile feedback via linear haptic motors (LHMs) has become crucial for enhancing user interaction in devices such as smartphones and gaming controllers. This study investigates the effect of cogging force on LHM performance. A theoretical model is developed using the Maxwell stress tensor to calculate electromagnetic force distributions. The force relationship has been derived to analyse the performance of LHM. Three experiments validate the effect of cogging force, which can be treated as a negative stiffness, reducing the mechanical stiffness of the system. A 4-magnet design is proposed to obtain a linear cogging force. An electromagnetic-mechanical (E-M) coupling model is used to obtain the displacement of LHM. The analysis result has a good agreement with experimental data. This work lays the groundwork for future LHM research.

Keywords: Cogging Force, Linear Haptic Motor, Electromagnetic-Mechanical Coupling, Maxwell Stress Tensor, Mechanical Stiffness

1. Introduction

In recent years, smartphones have changed people's lives with multiple functions. The linear haptic motor [1] is an important device in smartphones to provide haptic feedback.

In a previous study, Xu et al. [2] investigated the cogging force [3] on a balanced armature receiver and found that the cogging force is linearly distributed on a part of the armature. It can be considered a negative spring force and helps to reduce the stiffness of the mechanical system. Xu et al. considered the cogging force by modifying the mechanical properties to obtain the same vibration deformation. However, no exact spring stiffness or negative spring stiffness calculations were reported.

The cogging force occurs as a result of the interaction between the permanent magnet and ferromagnetic material in the rotor and stator, and it is typically an undesirable effect in permanent magnet motors because it can cause the rotor to vibrate or oscillate.

Most studies have focused on rotary motors [4] to analyse cogging and current forces. This leaves a gap in understanding how cogging and mechanical spring forces interact in LHMs.

Compared with existing research, the main contribution of this research is a detailed analysis and verification of the cogging force and current force effect in linear haptic motors [5-8]. A new design of the magnetic circuit is proposed to obtain a linear cogging force. The application of electromagnetic-mechanical coupling analysis is used for confirmation. This study had the goal of providing a new and improved understanding of the cogging force effect and its impact on the

performance of a linear motor, and the results of this research may contribute to the development of more efficient and effective linear motor systems.

2. Analysis method

2.1. Maxwell's equations

The Maxwell equations [3], as the fundamental equations of the electromagnetic field, are shown in:

$$\nabla \bullet \mathbf{E} = \frac{\rho}{\epsilon_0} \quad (1)$$

$$\nabla \bullet \mathbf{B} = 0 \quad (2)$$

$$\nabla \times \mathbf{B} = - \frac{\partial \mathbf{B}}{\partial t} \quad (3)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} \quad (4)$$

Maxwell's equations describe how electric and magnetic fields are generated and interact. Gauss's law Equation(1) for electricity determines the electric field distribution from a given charge density, while Gauss's law for magnetism Equation(2) establishes that magnetic fields have no sources or sinks and therefore form closed loops. Faraday's law Equation(3) of induction explains how a changing magnetic field induces an electric field, and the Ampère–Maxwell law Equation(4) describes how a magnetic field arises from an electric current and a changing electric field.

2.2. Maxwell's stress tension

The Maxwell stress tensor [4] can be used to calculate the forces exerted by electromagnetic fields on electromagnetic objects.

In this approach, the mover is enclosed by a closed surface S and computes the net electromagnetic force via a surface integral:

$$\vec{\mathbf{F}} = \oint \mathbf{T} \bullet \hat{\mathbf{n}} dS \quad (5)$$

Where $\vec{\mathbf{F}}$ is the resultant force and $\hat{\mathbf{n}}$ is the outward normal to the surface S .

$$T_{ij} = \frac{1}{\mu_0} (B_i B_j - \frac{1}{2} \delta_{ij} B^2) \quad (6)$$

$$\delta_{ij} = \begin{cases} 1 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases} \quad (7)$$

Where B_i and B_j are the components of the magnetic flux density, δ_{ij} is the Kronecker delta accounting for directionality given by Equation(7), and B is the magnetic flux density.

2.3. Force type

This section examines how these forces evolve with respect to the mover position and applied current, and how they contribute to the overall stiffness and performance of the motor system.

2.3.1. Cogging force

The cogging force, also called the no-current force, arises predominantly from the interaction between permanent magnets on the mover and the stator's magnetic materials. It can be expressed as the spatial derivative of the stored magnetic energy in the system.

In one-dimensional motion, the cogging force is obtained from the energy gradient:

$$F_{\text{cog}}(x) = \frac{dU_{\text{max}}(x)}{dx} \quad (8)$$

Where $U_{\text{max}}(x)$ is the total magnetic energy as a function of position x . The cogging force magnitude depends on displacement.

To measure the cogging force separately, the mover is attached to a helical spring. Fig.a shows the equilibrium configuration of this setup, where no additional force is applied. By displacing the mover from this equilibrium position, the cogging force increases linearly: the spring force changes due to the displacement, while the cogging force appears as an additional force.

To understand the relationship between cogging force and spring force, the magnetic configuration, including a permanent magnet, a Ferromagnetic material and a mechanical system, is shown in Figure 1.

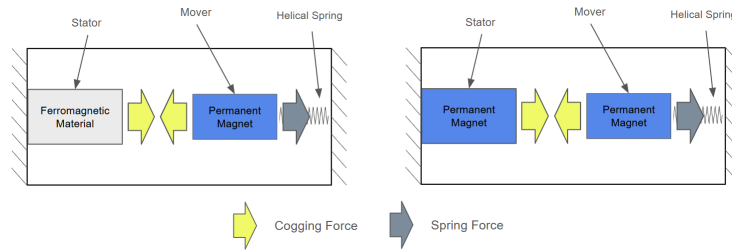


Figure 1. The magnetic configuration

In this configuration, the force exerted on the mover by the spring and F_{cog} is the cogging force resisting the motion. By Newton's third law, the net force on the mover is the sum of these two contributions:

$$F_{\text{net}} = F_{\text{Spring}} + F_{\text{cog}} \quad (9)$$

$$F_{\text{net}} = -(K_{\text{Spring}} - K_{\text{cog}})x \quad (10)$$

Where spring force is linear with displacement, $F_{\text{spring}} = -K_{\text{Spring}}x$, K_{Spring} being the spring stiffness, and the cogging force, F_{cog} . The cogging force can be treated as a negative spring force.

2.3.2. Current force

The current force is the electromagnetic force generated by the electrical current passing through a coil. The current force can be divided into two types based on working principles: the Lorentz force and the solenoid force.

2.3.2.1. Lorentz force

The direction of the Lorentz force can be obtained by the right-hand rule, where the force acts perpendicular to both electrical and magnetic fields. The force is generated by the following equation:

$$\vec{F} = I(\vec{L} \times \vec{B}) \quad (11)$$

2.3.2.2. Solenoid force

The solenoid force results from position-dependent magnetic energy in the coils, where inductance L varies with the mover–stator position. The mechanical force is:

$$F_s = \alpha I^2 \quad (12)$$

$$\alpha = \frac{1}{2} \frac{dL}{dx} \quad (13)$$

This shows the force, F_s , is proportional to the square of the current, I , and independent of its direction, making it unidirectional.

The relationship between the current force, solenoid force, and Lorentz force is given by:

$$F_{\text{current}} = F_{\text{Lorentz}} + F_s \quad (14)$$

These current forces superimpose onto cogging forces, producing a net displacement force when current is applied.

$$F_{\text{total}} = F_{\text{current}} + F_{\text{cog}} \quad (15)$$

2.4. Electromagnetic–mechanical coupling

The electromagnetic–mechanical (E–M) coupling analysis method was employed to investigate the dynamic behaviour of the linear haptic actuator by modelling the mutual interaction between electrical excitation and mechanical response.

The governing electrical equation of the actuator coil is given by:

$$V_{\text{input}} = iR_e + L_e \dot{i} + K_b \dot{x} \quad (16)$$

The current, i , can then be derived as:

$$i = \frac{V_{\text{input}} - K_b \dot{x}}{R_e} \quad (17)$$

V_{input} , R_e , L_e , K_b represents the applied voltage, electrical resistance, inductance of the coil and the back electromotive force (EMF), respectfully.

Simultaneously, the mechanical dynamics of the mover were modelled using the forced-vibration equation:

$$[M]\ddot{x} + [C]\dot{x} + [K]x = K_f i \quad (18)$$

Where $[M]$, $[C]$, and $[K]$ represent the mass, damping, and stiffness matrices, respectively. The right-hand side represents the electromagnetic driving force due to the current input.

By combining the voltage equation and the force vibration equation, the E-M coupling equation is obtained as shown in Equation(19).

$$[M]\ddot{x} + \left([C] + \frac{K_f K_b}{R_e} \right) \dot{x} + [K]x = \frac{K_f}{R_e} V_{\text{input}} \quad (19)$$

In the forward coupling direction, the coil current generates a magnetic field that applies force to the mover, producing mechanical motion. This is described by the term $K_f i$ in the mechanical domain. In the backwards coupling direction, the mover's motion through the magnetic field induces a back-EMF, proportional to velocity, that opposes the input voltage. This feedback is captured by the $K_b \dot{x}$ term in the electrical equation. The presence of these terms reflects that the system's electrical and mechanical states are tightly interlinked.

To solve the coupling system and evaluate force generation, displacement under various current inputs, simulations were conducted using COMSOL Multiphysics. This enabled simultaneous resolution of the magnetic field distribution and mechanical motion, including non-linearity due to magnetic saturation. The goal of the E–M coupling analysis is to accurately predict motor behaviour across a range of operating conditions and to provide a foundation for closed-loop control design based on realistic requirements.

3. Experiment

The following experiments aim to characterise the effect of cogging and current forces on a linear haptic motor system. Three distinct experiments were conducted to:

Case 1: Measure the pure mechanical stiffness of a spring system to establish a baseline.

Case 2: Quantify the effect of cogging force on mechanical stiffness in the absence of current

Case 3: Evaluate the combined influence of cogging force and current force on system behaviour

These objectives support the new design and optimisation of the motor by providing quantitative insights into force-displacement relationships, validated through COMSOL Multiphysics simulations.

3.1. Setup and material

3.1.1. Setup

A 3D-printed vertical framework is designed to constrain all components along a single axis, ensuring coaxial alignment between the spring, mover, and electromagnet holder to eliminate off-axis disturbances.

3.1.2. Parts

Table 1. Details of the framework are listed in the Table 1. Including description and specification

Items	Material	Specification	Description
Mounting Frame	Aluminium	700 x 150 x 150 mm	Rigid frame provides support to the spring and electromagnetic holder
Electromagnet Holder	Aluminium + PLA	100 x 150 x 150 mm	Heat-resistant mount, connected to the lower end of the framework, used to secure the electromagnet and maintain alignment with the permanent magnet
Spring	Steel	Diameter: 1.2 mm Width: 20 mm Length: 150 mm	Ovalic spring used to both model pure mechanical systems, and provide a connection to the mover
Calibrated Masses	Steel	Types: 50 g, 100 g Max: 500 g	A set of masses added to the mass holder is used to provide force to extend the spring
Mass Holder	PLA, 3D-Printed Structure	60 x 70 x 40 mm	Part of the mover, used to secure the calibrated masses
Permanent Magnet Holder	PLA, 3D-Printed Structure	60 x 40 x 20 mm	Part of the mover, used to secure the permanent magnet and maintain alignment with the electromagnet
Tape Measures	Plastic	0 - 5 meter, 1 mm	Tape measures are used for the measurement of the extension of the spring
Power Supply	-	0 - 20 V, 1 A	Used as current provider for electromagnet

Table 2. The mechanical properties of permanent magnet, electromagnetic material and coil are listed in Table 2

Parts	Material	Density	Young's modulus	Poisson's ratio
Permanent Magnets	N45H	7.5 g/cm ³	150-200 GPa	0.24
Iron Core	SPCC	7800 kg/m ³	200 GPa	0.26
Coils	Copper	8940 kg/m ³	110-126 GPa	0.33

The spring is mounted vertically to the upper end of the framework, with the lower end attached to the mover, consisting of a mass holder and a permanent magnetic holder. A tape measure was positioned along the vertical framework to measure the spring's extension along its axis. Complete experimental setup illustrated in Figure 2.

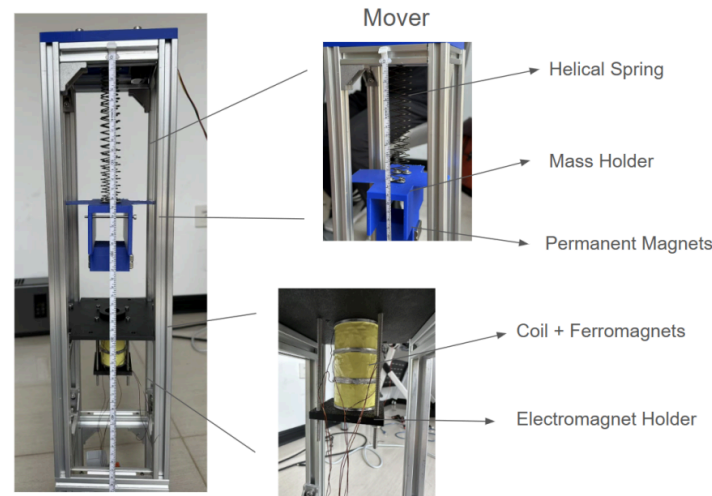


Figure 2. Experimental setup

Calibrated masses were incrementally added to the mass holder, ranging from 50 g to 250 g, corresponding to forces of 0.491 N to 2.452 N (using $g = 9.81 \text{ m/s}^2$). The laser displacement sensor measured the resulting extension from the spring's equilibrium length (L_0). Measurements were taken after allowing the system to stabilise for 10 s to dampen oscillations.

3.2. Experiment

3.2.1. Case 1: pure spring system

In the first experiment, the aim is to measure spring force and identify spring stiffness; therefore, no magnetic fields are involved. Permanent magnets are added to the holders to maintain a constant initial position. Illustrated as follows:

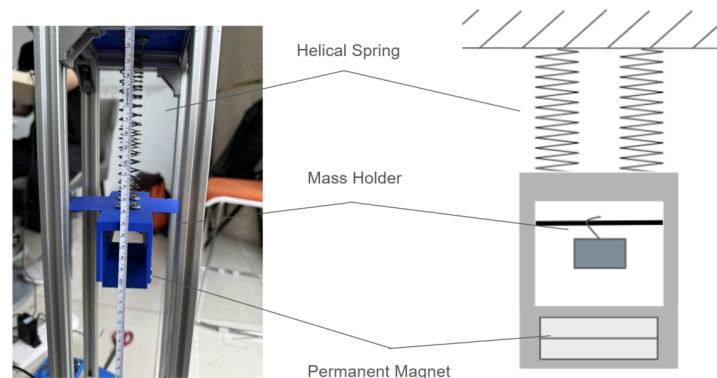


Figure 3. Experimental setup (case1)

Pre-load displacement was measured and subtracted from all subsequent readings to ensure the force–displacement relationship reflects only incremental changes. Calibrated masses were incrementally added from 100g to 500g. Displacement and forces are then collected and graphed as shown in the following Figure 4. Analysis experimental results is described in section 3.3.

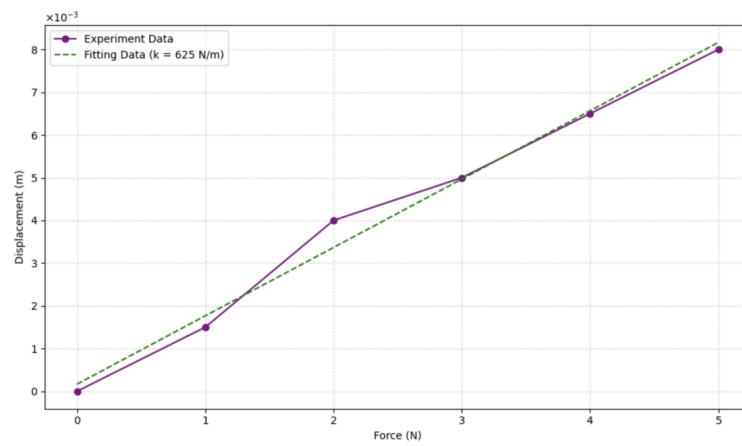


Figure 4. Case 1 results

3.2.2. Hybrid system (spring & cogging)

In the second experiment, the aim is to validate the stiffness effect of cogging force with no current influence. The experimental configuration is illustrated in Fig.

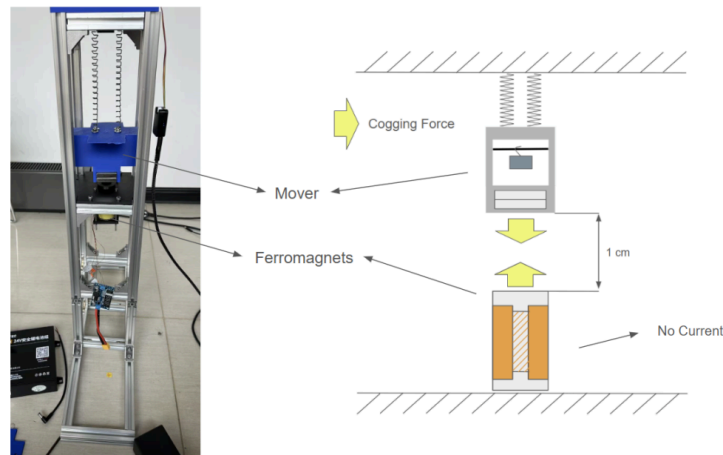


Figure 5. Experimental setup (case 2)

The displacement and force of case 2 are shown in Figure 6.

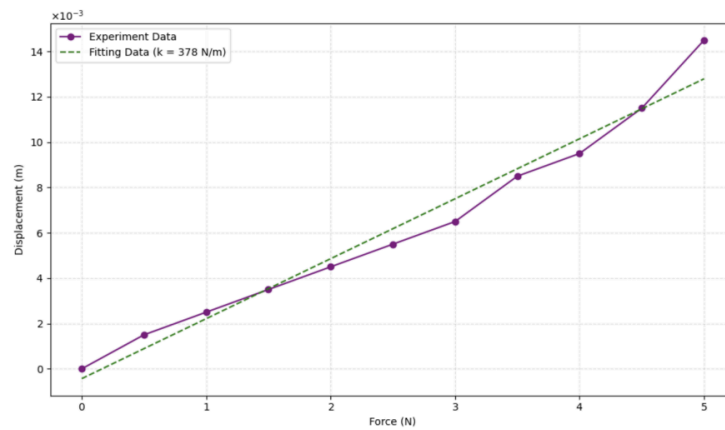


Figure 6. Case 2 results

3.2.3. Hybrid system (spring & cogging & current)

In the third experiment, the objective was to measure the displacement of the system under the combined influence of the cogging force and the current force. Varying current was supplied to the electromagnet from 0A to 20A, in step of 2A, using a regulated DC power source. setup is illustrated in Figure 7.

When electrical current is into the coil, the magnetic material within the coil can be treated as an electromagnet.

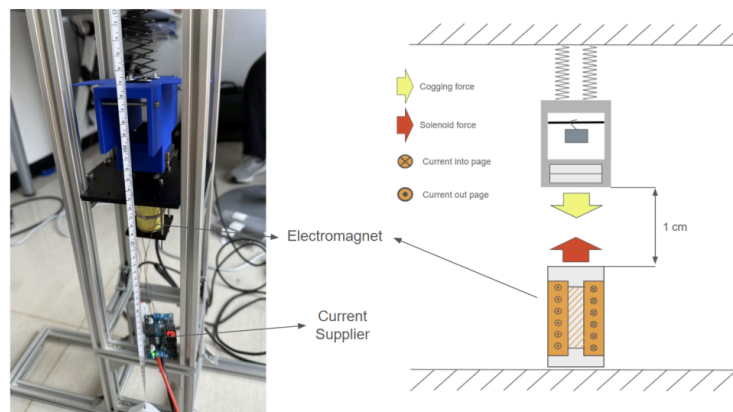


Figure 7. Experimental setup (case 3)

Displacement and force results are collected at each testing current, with their effect isolated and displayed as Figure 8:

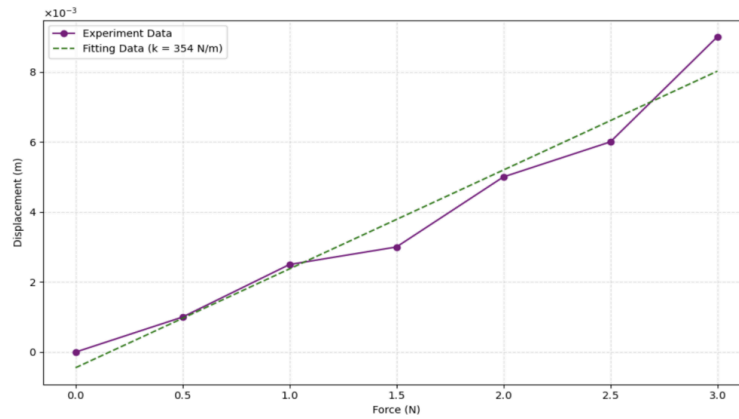


Figure 8. Case 3 results

3.3. Results and discussion

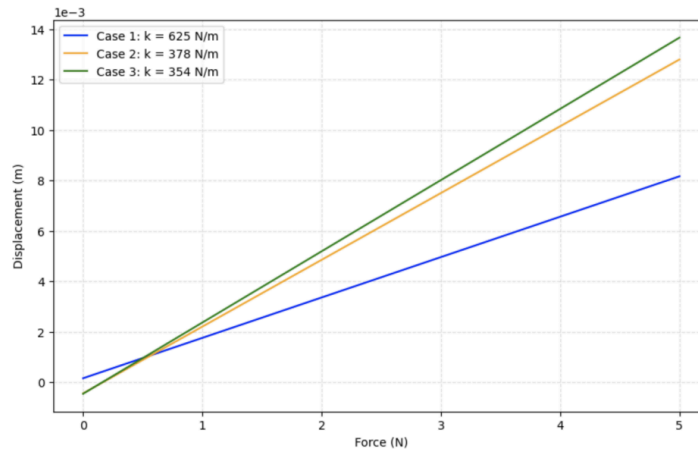


Figure 9. Combined results of case 1 - 3

Figure 9 illustrates the linear relationship between displacement (X-axis) and force (Y-axis), where the inverse slope of the fitted line represents the system stiffness. In Case 2, the cogging force exhibits a linear dependence on displacement, effectively reducing the overall mechanical stiffness. This behaviour indicates that the cogging force can be modelled as a negative spring force. The effect of the cogging force was validated through experimental results. According to measured data, mechanical spring stiffness is 625N/m, and shows a reduction of 378N/m after adding cogging force, which means cogging stiffness in this system is equal to 247N/m. This magnitude of cogging force is determined by the magnetic circuit design.

Comparing case 2 and 3, the current force added to the coil makes the mover displace a larger displacement under less force when applied, showing increased attraction force between the mover and stator. Experimental data shows a decrease between 378 to 354.4N/m. This additional force is hence controlled by current, allowing adjustments and control over displacement. Case 3 extension shows the linear relation between current and controlled current force, as shown in Figure 10.

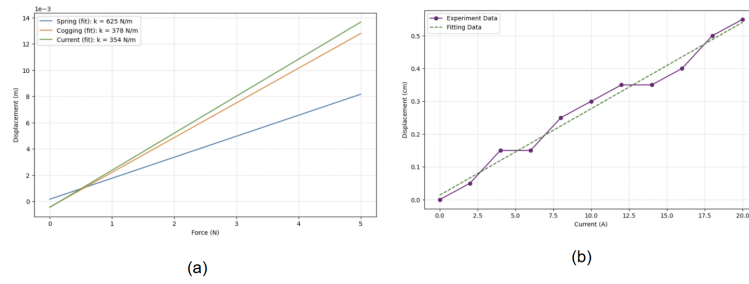


Figure 10. Case 3-extended results

4. New design and simulation

To design the haptic motor with linear cogging force, the 2-magnet structures are proposed, and the vertical and horizontal configurations are shown in the Figure 11 (a) and Figure 11 (b), respectively. The finite element method is employed through simulation to perform the magnetic analysis to obtain the cogging force.

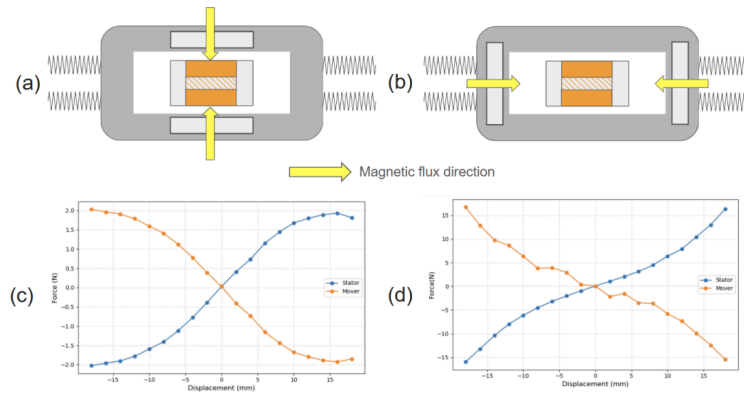


Figure 11. Vertical 2-magnets arrangement (b) Horizontal 2-magnets arrangement (c) Vertical arrangement results (d) Horizontal arrangement results

Simulation results, Figure 11 (c), Figure 11 (d), show weak control of the Cogging force, causing non-linear curvatures at maximum displacements.

A new 4-magnet structure is proposed using the same cogging force simulation. Results show a better linear relation between force and displacement shown in Figure 12.

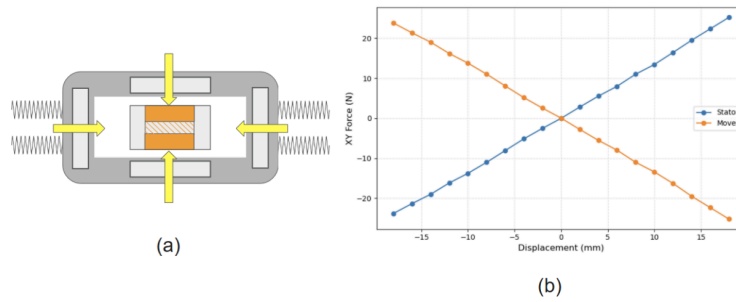


Figure 12. (a) 4-magnets arrangements (b) 4-magnets arrangement results

Hence combined 4 magnets combined in both the x and y axes are used in the experiment testing. To obtain the force factor, a current force analysis is produced, as shown in Figure 13.

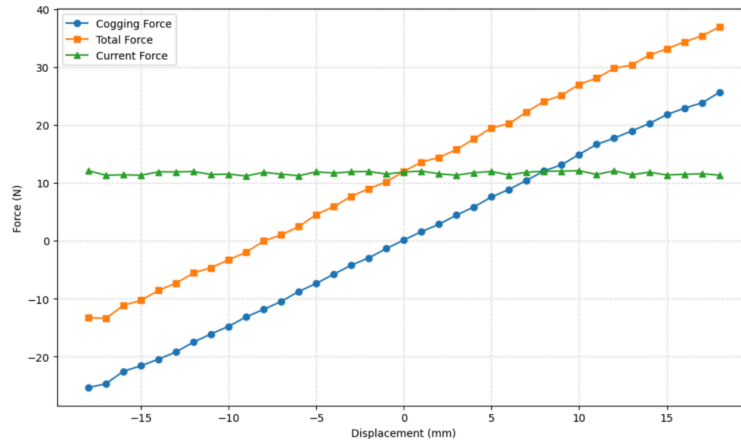


Figure 13. Combined results: cogging force, current force, and total force

Force factor is the ratio between the current force and the current, which can be treated as a constant value, determined by the magnetic circuit and coil design. The force factor of our system is 11.65 N/A

Electromagnetic and mechanical coupling analysis is employed to calculate the displacement of the linear haptic motor in the frequency domain. In input voltage is 15V. The simulated result is shown in Figure 16.

4.1. Experiment

The experimental setup consists of a mover with 4 magnets arranged in both horizontal and vertical axes, an electromagnet is fixed at the centre of the mover. Total effective stiffness is measured at 875.23 N/m. Hence resonance frequency can be calculated as 13.74 Hz. Figure 14 shows the full experiment setup.

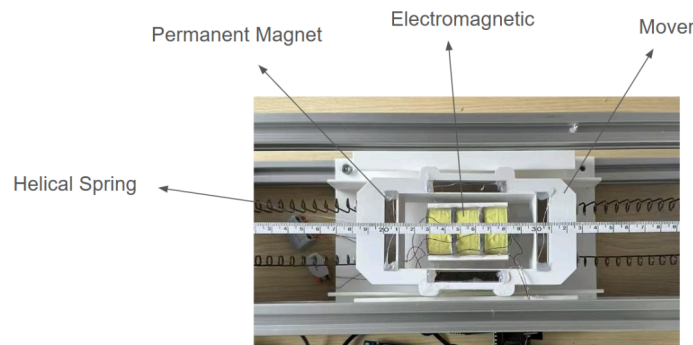


Figure 14. Experimental setup for 4-magnets arrangements

A sinusoidal alternating current of constant amplitude (1 A) was applied to the fixed electromagnetic at three different voltage levels: 10 V, 15 V, and 20 V. For each voltage level, the frequency of the input signal was varied across 1 Hz, 5 Hz, 10 Hz, 15 Hz, 20 Hz, and 50 Hz. The displacement of the mover is recorded using a slow-motion camera. The camera was positioned orthogonally to the direction of motion to minimise parallax error. The maximum displacement (peak-to-peak movement) was measured manually from the recorded footage using video analysis software with calibrated scale markers in frames.

All trials were conducted under identical mechanical and thermal conditions to minimise environmental variation. Between each trial, the system was allowed to return to its equilibrium position to ensure consistency.

4.2. Result and discussion

Results of maximum displacement are recorded at varying frequencies for three input voltages: 10 V, 15 V, and 20 V. Shown in Figure 15.

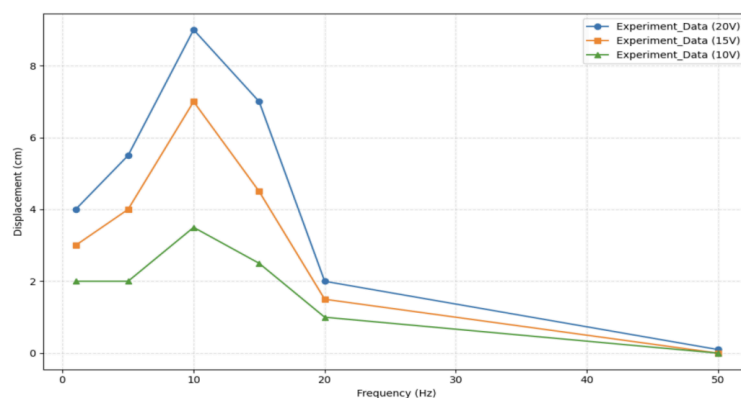


Figure 15. Maximum frequency results at different voltages for 4-magnets arrangement setup

Experimental results suggest that increasing current affects only the current force, as indicated by the increase in displacement. The resonance frequency remains constant across all test conditions, indicating that the system's effective stiffness is independent of the current level.

As expected, increasing the voltage leads to a higher current force, which in turn results in greater displacements. This relationship between input voltage and displacement appears to be linear.

Data comparison between experiment data and simulation data at 15V is shown in the Figure 16, with results highly identical.

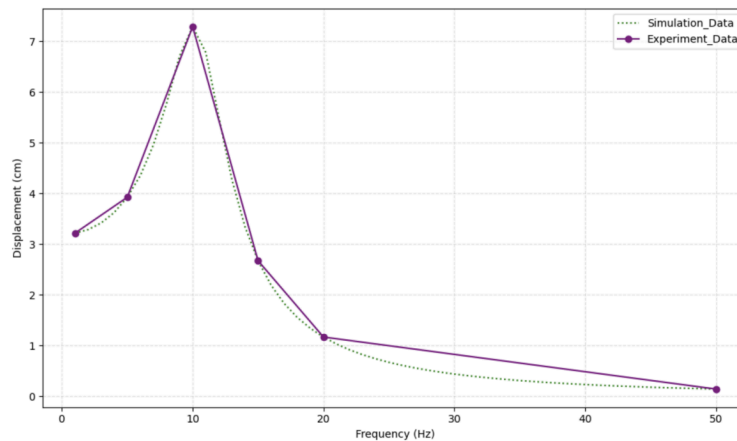


Figure 16. Experimental vs simulated results

5. Conclusion

In this study, a new magnetic circuit design incorporating a linear cogging force demonstrated clear advantages over conventional designs that rely solely on mechanical springs. Using Maxwell's stress tensor, the relationship between force and displacement was carefully examined. The magnetic circuit ensured a linear, precisely calculated, cogging force across a displacement range of 18 to 18 mm, enabling an electromagnetic-mechanical coupling analysis to identify the motor's performance. These findings highlight the potential to enhance haptic motor performance through the integration of innovative electromagnetic and mechanical structural design.

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