Modelling and Characterisation of a Novel Two-Finger Variable Reluctance Gripper

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***Abstract* - Variable reluctance (VR) actuator has a simple and robust structure. VR actuator does not have a permanent magnet. It is low-cost; easy-to-manufacture, highly reliable, and can operate in hostile temperatures. However, it is inherently nonlinear, and is difficult to control and operate as a proportional device. With the advancement of digital signal processing and power electronic drives in recent years, VR actuators have redrawn research interests.**

The paper describes the investigation and development of a novel two-finger gripper using VR technology. A novel two-finger VR gripper is proposed and fabricated. Measurement and characterization of the actuator is carried out and a mathematical model of the actuator is constructed. Finally, model is simulated and it is verified with experimental results. The actuator exhibits pseudo-linear properties and it is suitable for position and force control applications. The results show that the proposed actuator is an ideal replacement for the higher-cost and less-robust permanent magnet actuators.

I. INTRODUCTION

Force Control of robotic gripping has been the subject of numerous robotic researchers. Numerous grippers were designed for specific force control applications as cited in [1-4]. Numerous actuators are employed, namely, DC motors, PZT, thermal and pneumatic actuators. However, the use of variable reluctance technology is still unexplored.

Thermal grippers suffer from slow force responses and small opening areas [1]. Pneumatic grippers are commonly found in high force applications but inherent slow force responses like thermal actuators [2]. Voice coil or DC motors can provide an alternative solution [3]. With permanent magnet, actuators tend to be costly and not suitable for hazardous conditions. Piezoelectric grippers tend to provide a highly accurate force but small opening areas and low force [4]. The proposed actuator enjoys few mechanical components, fast force response and high precision position and force control.

Variable Reluctance (VR) actuator has a simple and robust structure. With the absence of permanent magnet, it tends to have a lower inertia and a higher temperature operating range. The stator windings are easy to fabricate and actuator has a very low manufacturing cost. However, VR actuator inherits nonlinear properties and thus increases its control complexity [5].

The main objective of the project is to design and fabricate a novel two-finger VR gripper with pseudo-linear electrical and magnetic characteristics. A mathematical model of the actuator has to be developed in which close looped position and force control can be employed. Measurements are conducted for the two-finger VR actuator characterization and the model is verified.

This paper presents a novel two-finger gripper with pseudo-linear magnetic properties suitable for position and force control applications. The gripper is unique for the employment of variable reluctance technology. This paper describes the structure of the proposed VR gripper. Mathematical model and characterization methods are presented. With the flux linkage measurement, a simulation model is constructed. Simulation model is verified with experimental results.

II. CONSTRUCTION OF THE MOTION ACTUATOR

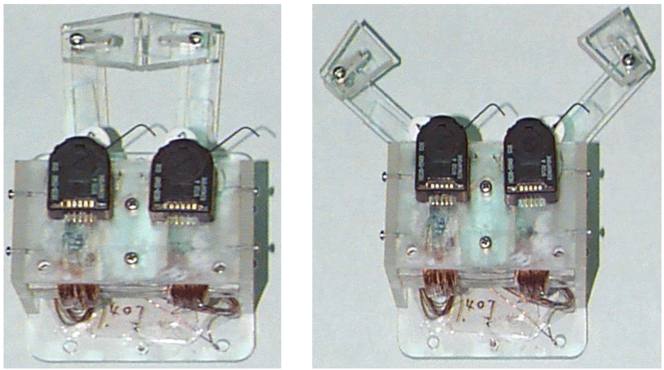
(a) at aligned (grasp) position (b) at unaligned (release) position

Fig. 1. The VR Finger Gripper

Fig. 1 shows the VR Gripper used in the project. It consists of two rotary elements, each attached to a finger. The actuator contains two coils with 400 turn windings each.

The moving rotors are mounted onto two individual shafts, whose axes are normal to the plane of the diagram, so that it can rotate freely between the poles of the stator. Both the rotors and stators are made up of laminated mild steel to reduce eddy current effects.

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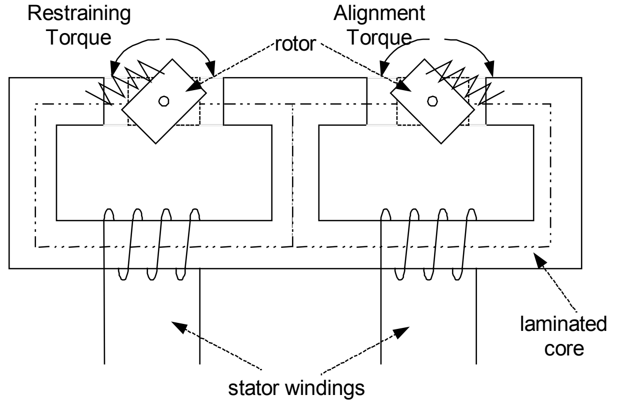

Fig. 2. Top View of Rotary VR Gripper

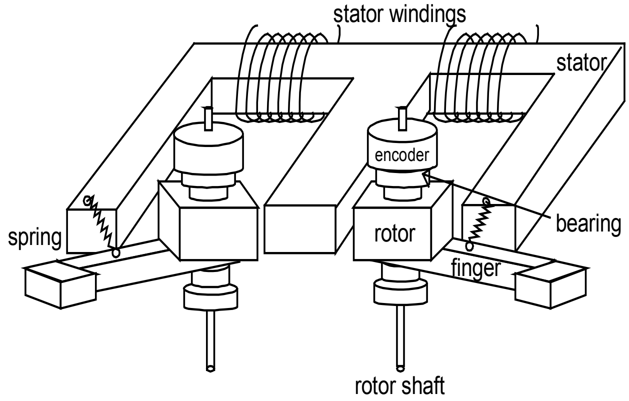

Fig. 3. Side View of Rotary VR Gripper.

Two fingers of the gripper, shown in Fig. 2, are 90mm long and spring loaded, which allows bi-directional movement from the single direction excitation of the coils. When currents are applied to the stator windings, the rotors rotate away from initial positions to reduce their reluctance by alignment torque. The rotors eventually stay still when alignment torque comes into equilibrium with restraining torque provided by the spring. When the fingers rotate by 40°, the fingertips would be closed and the rotors are in fully aligned positions. Incremental rotary encoders are mounted on the shafts to measure rotor positions with a resolution of 0.35°.

III. MATHEMATICAL MODEL OF THE PROJECT VR GRIPPER

The motor characteristics can be described by equations (1)-(2):

$$J_j \frac{d^2\theta_j}{dt^2} = T_j - K_{sj}\theta_j \Bigg|_{j=1,2} \qquad (1)$$

$$T_j = \frac{d\lambda_{jj}}{d\theta_j} i_j + \frac{d\lambda_{jk}}{d\theta_j} i_k \Bigg|_{j=1,2;k=2,1} \qquad (2)$$

where J_j, T_j, K_{sj}, θ_j, λ_{jj}, λ_{jk} and i_j are rotor inertia, motor torque, spring constant, rotor angle, self flux linkage, mutual flux linkage and stator current respectively.

Note that, in the equations, the flux linkage has a relation with current and position. With accurate measurement of flux linkage λ, i.e. λ_{jj} and λ_{jk}, an accurate model for the VR gripper can be obtained.

IV. EXPERIMENT

When a flux passes through a coil with N_s turns, an electromotive force (EMF), $e(t)$, would be induced. Flux $\Phi(t)$ can be expressed as :

$$\Phi(t) = -\frac{1}{N_s} \quad e(t)\cdot dt \qquad (3)$$

Flux linkage $\lambda(t)$ can be expressed as

$$\lambda(t) = N \cdot \Phi(t) \qquad (4)$$

where N is the number of turns of the stator winding.

The flux linkage curves $\lambda(\theta,i)$ need to be obtained at different positions and current levels. Flux measurement method similar to [7, 8] is employed.

Motor windings are excited with an AC current with the rotor kept still by a fixture. Frequency is chosen at 50Hz for simplicity since frequency is independent from the flux measurement [9]. Different current levels can be adjusted with an isolated autotransformer. Current is measured with a current resistor. Search coils are wounded around the stator to determine the self and mutual flux linkage. Different current levels (0.4A - 2.8A) and rotor positions, 0° - 40° away from full-aligned positions are measured. The overall measurement setup is shown in Fig. 3. Results are shown in Fig 4-9.

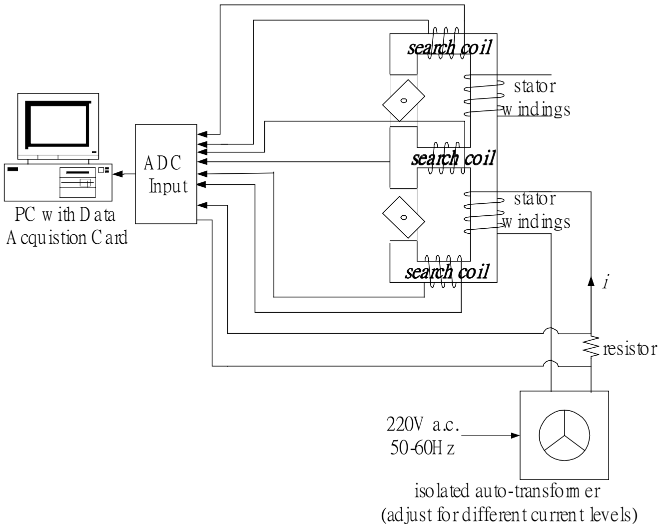

Fig. 4. Experimental Setup for Flux Linkage Measurement

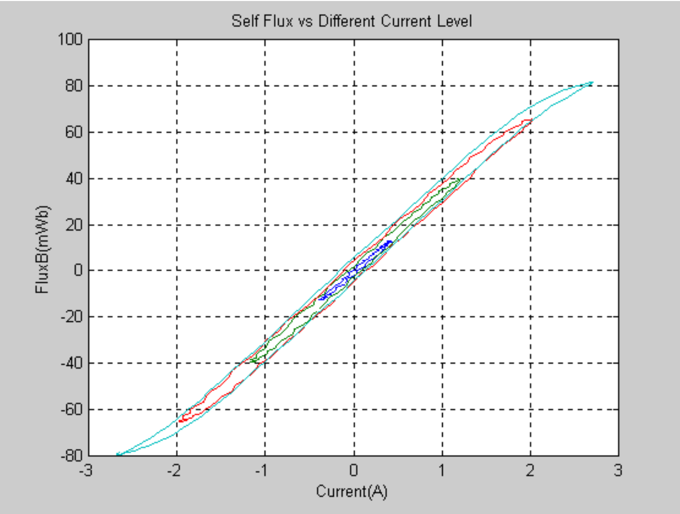

Fig. 5. Self Flux linkage versus different current level

Fig. 6. Self Flux linkage versus different rotor position

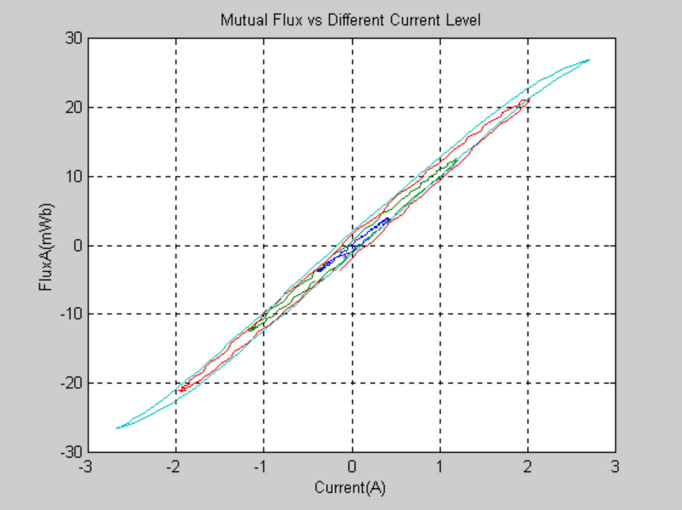

Fig. 7. Mutual Flux linkage versus different current level

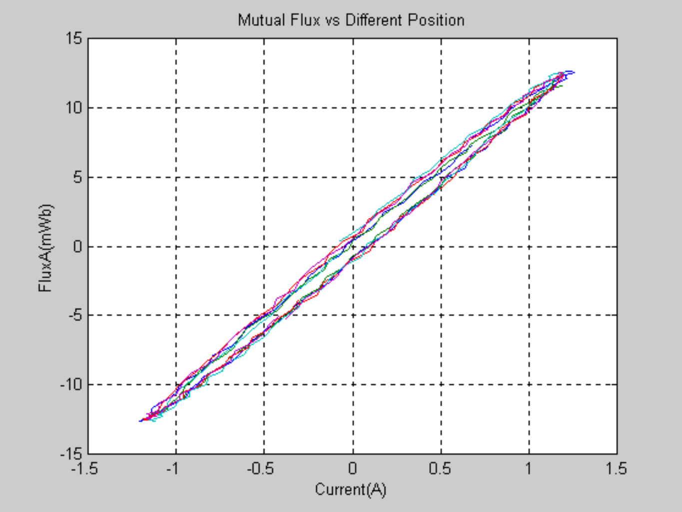

Fig. 8. Mutual Flux linkage versus different rotor position

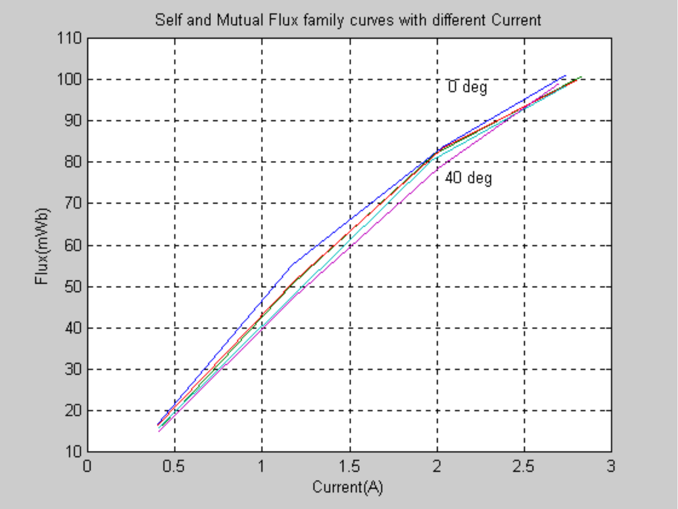

Fig. 9. Total Flux linkage family curves with different current levels

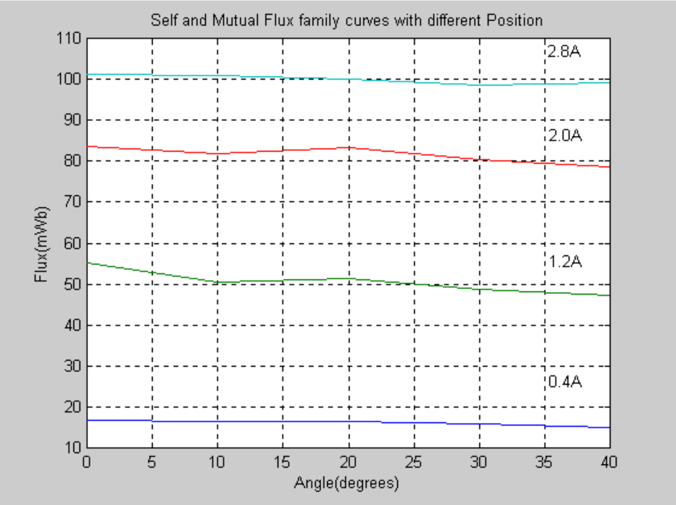

Fig. 10. Total Flux linkage family curves with different rotor positions

Fig. 5–6 and 7-8 show self and mutual flux linkage characteristics versus against different input current and rotor positions respectively. Mutual flux linkage is only 30% of self flux linkage.

Fig. 9-10 show the total flux linkage varies quite significantly with current levels changes, but less so for rotor position changes. The VR gripper stays within the linear region below 2A, and no significant flux saturation is found.

V. MODELLING

Fig. 11 shows the equivalent VR Gripper magnetic circuit representation. The stator coils, rotor and E-core common path can be represented by MMF sources, variable reluctance and fixed reluctance.

Due to the symmetrical structure of the actuator, the excitation currents in gripping motion in both stator windings and the MMF sources, Φ_l and Φ_r are assumed to be equal. Therefore, self inductance of both rotors with magnetic flux path ABD and CBD are equal. Mutual inductance would cancel each other out since they are in opposite directions.

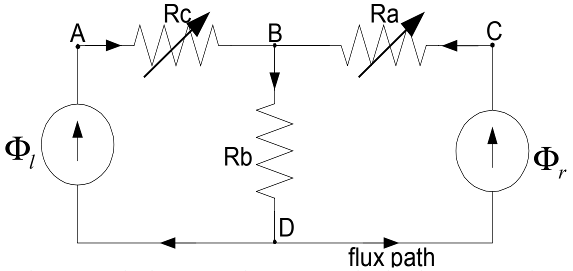

Fig. 11. Equivalent VR Gripper magnetic circuit representation

Thus, the linear motor force model can be expressed as equation (5) below.

$$F = \frac{1}{2l} i^2 L \sin(2\theta) \qquad (5)$$

where F, i, L, l and θ are rotor force, excitation current, self inductance, finger length and rotor angle [10]. In Fig.12, the 3D flux linkage profile is constructed with a 3rd order polynomial surface fitting.

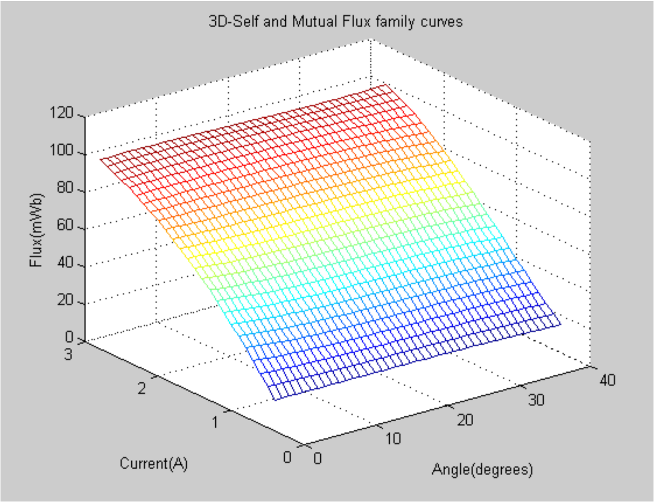

Fig. 12. 3D-Flux linkage profile of VR Gripper

Besides, with the experimental data obtained previously, force profile can be constructed from equation (5) as shown in Fig. 13.

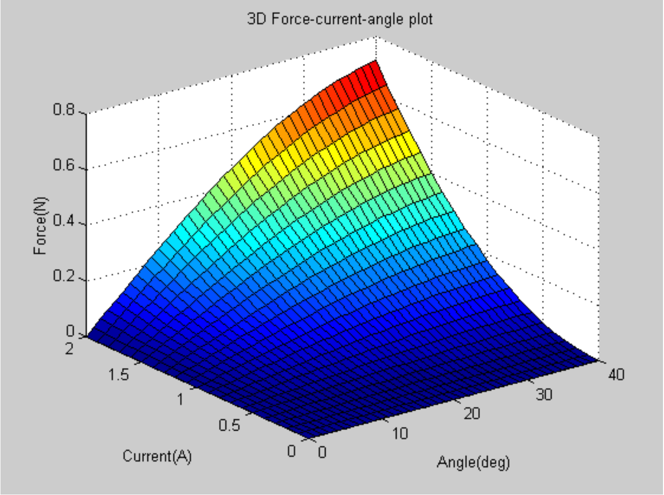

Fig. 13. 3D Force profile of VR Gripper

VI. FORCE PROFILE VERIFICATION

The force model is verified with static force measurement. In Fig. 14, a force sensor is mounted at the fingertip for force measurement. Different levels of DC current, i, are injected into both stator windings. Force is applied perpendicularly towards the force sensor. Force induced by is measured at different rotor positions.

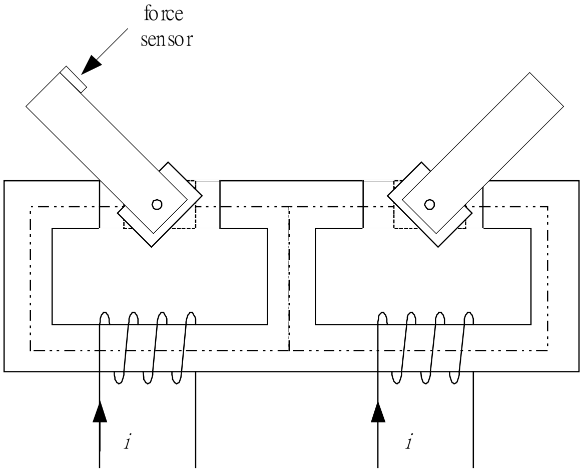

Fig. 14. Force Model Verification Setup

As shown in below figure, the force model is highly consistent with the measured data.

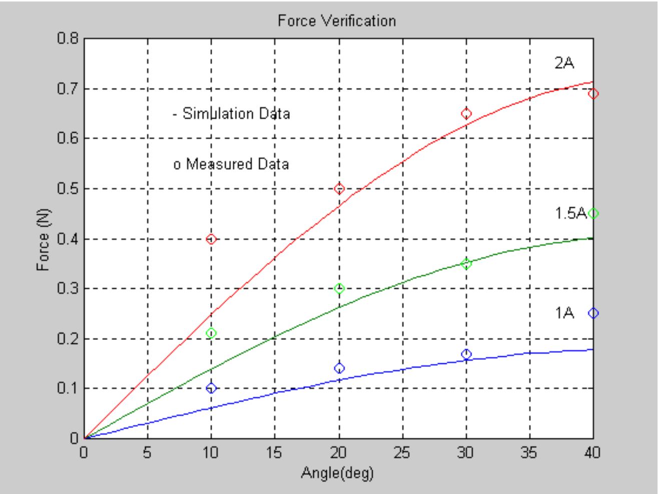

Fig. 15. Force Model Verification

VII. CONCLUSION

A novel two-finger gripper based on variable reluctance technology has been designed and fabricated. The resulting actuator is robust and simple, and it is suitable for hazardous environment. With the absence of permanent magnet, the manufacturing cost and difficulty are much reduced.

Self and mutual flux linkages are measured and 3D-flux linkage profiles are generated with a 3rd order polynomial surface fitting. The actuator inherits a non-uniform force profile as a reluctance actuator. However, its operating region is below the flux saturation region; thus most of the nonlinear properties of flux characteristics are avoided. A dynamic model of the VR Gripper is developed which is further verified with the static force measurement.

With the dynamic model developed, the VR Gripper is suitable for high precision position and force control applications.

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