MODELLING AND CHARACTERISATION OF HIGH PERFORMANCE VARIABLE RELUCTANCE FINGER GRIPPER

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Abstract

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 non-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.

Keywords
Finger Gripper, variable reluctance, non-linear modelling.

1 INTRODUCTION

Gripper mechanism plays an important role in factory automation, industry applications and robotics. Various finger grippers have emerged to serve numerous applications. Actuators ranging from traditional DC motors and voice coils, to thermal and pneumatics are employed. Recently, electro-static and piezoelectric grippers were also designed to enrich the scope. However, application of variable reluctance technology is remained unexplored.

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 non-linear, and is difficult to control and operate as a proportional device. With the advancement of digital signal processor (DSP) and power electronic drives in recent years, VR actuators have redrawn research interests.

Due to its unique property, VR actuator can easily operate in saturation region. Unlike conventional voice coils and DC motors, due to its inherent non-linear properties, modelling of VR motor plays an important role. Without a suitable non-linear model and linearization, traditional control algorithm responses would result in large torque ripple and poor position tracking.

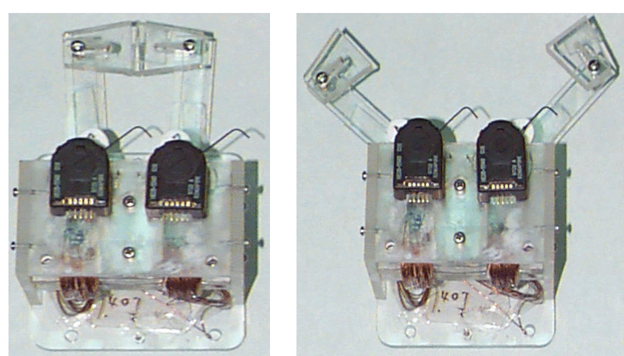
The main objective of the project is to design and fabricate a novel two-finger VR gripper. A mathematical model of the actuator has to be developed in which close looped position and force control can be employed. Measurements are conducted for the two-finger VR actuator characterization and the model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

This paper presents a novel two-finger gripper 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.

2 CONTENT

2.1 Construction Of VR Gripper

Figure 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.



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

Figure 1: The VR Finger Gripper

The moving rotors are mounted onto two individual shafts, whose axes are normal to the plane of the diagram, so that it may 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.

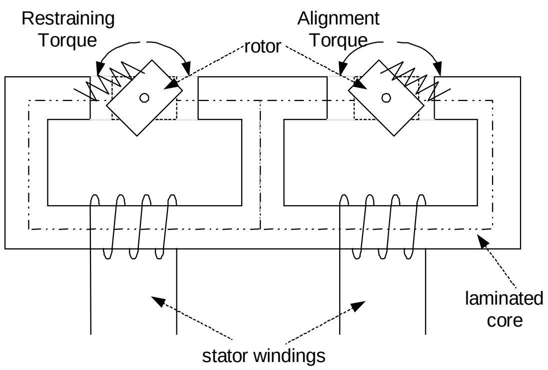


Figure 2: Top View of Rotary VR Gripper

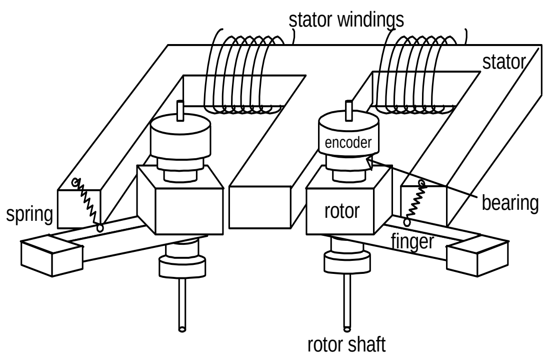


Figure 3: Side View of Rotary VR Gripper.

Two fingers of the gripper, shown in Figure 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°.

2.2 Mathematical Model

The motor characteristics can be described by equations below [5-6]:

$$J_j \frac{d^2\theta_j}{dt^2} = T_j - K_{sj}\theta_j \Big|_{j=1,2} \tag{1}$$

$$T_j = \frac{d\lambda_{jj}}{d\theta_j} i_j + \frac{d\lambda_{jk}}{d\theta_j} i_k \Big|_{j=1,2;k=2,1} \tag{2}$$

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.

On the electrical side, the motor can be represented as a resistive and inductive structure. Its voltage equation can be expressed as:

$$V = Ri + \frac{d\lambda}{dt} \tag{3}$$

where V, R *and* λ are terminal voltage, coil resistance and flux linkage respectively. Therefore, the voltage equation can be rewritten as:

$$V_j = R_j i_j + \frac{d\lambda_{je}}{dt} + \frac{d\lambda_{jj}}{dt} + \frac{d\lambda_{jk}}{dt} \Big|_{j=1,2;k=2,1} \tag{4}$$

where λ_{je} is the leakage flux.

Note that, in the above equations [1-4], the flux linkage has a relation with current and position. With accurate flux measurement, an accurate model for the VR gripper can be obtained.

2.3 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

$$\Phi(t) = -\frac{1}{N_s}\int e(t) \cdot dt \tag{5}$$

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

$$\lambda(t) = N \cdot \Phi(t) \tag{6}$$

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, mutual and leakage flux linkage. Different current levels (0.5A – 4.0A) and rotor positions, 0° - 70° away from full-aligned positions are measured. The overall measurement setup is shown in Figure 3.

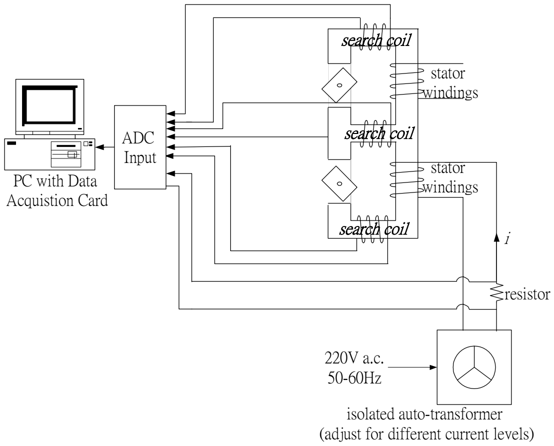


Figure 4: Experimental Setup for Flux Linkage Measurement

2.4 Results

Figures below shows the flux linkage relationships against different rotor positions and current levels respectively.

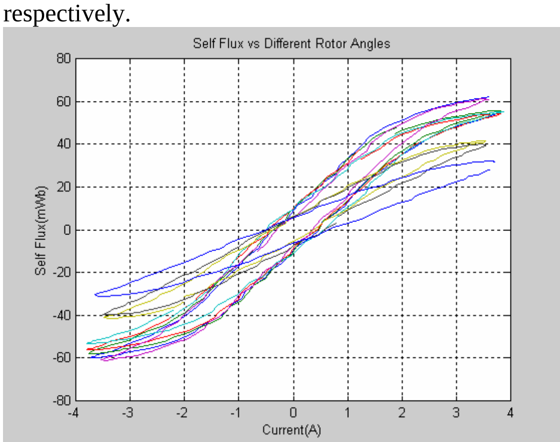


Figure 5: Self Flux linkage versus different rotor positions

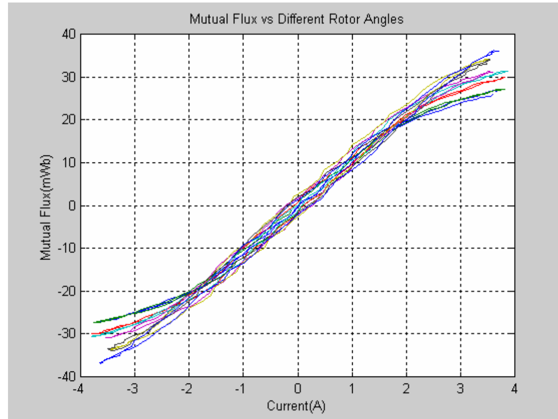


Figure 6: Mutual Flux linkage versus different rotor positions

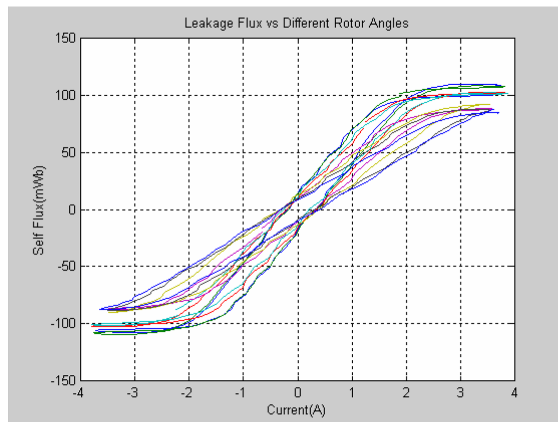


Figure 7: Leakage Flux linkage versus different rotor positions

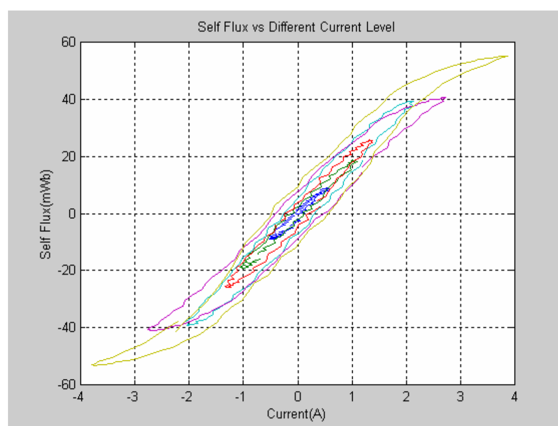


Figure 8. Self Flux linkage versus different current level

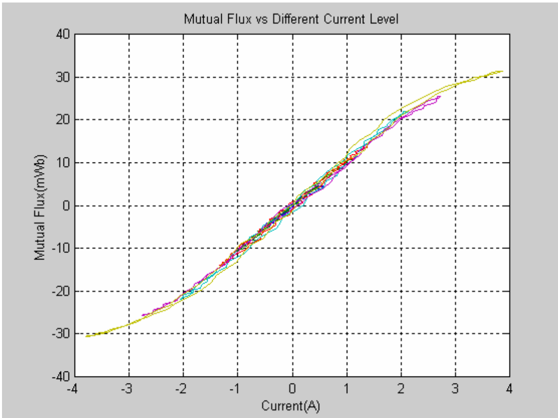


Figure 9. Mutual Flux linkage versus different current level

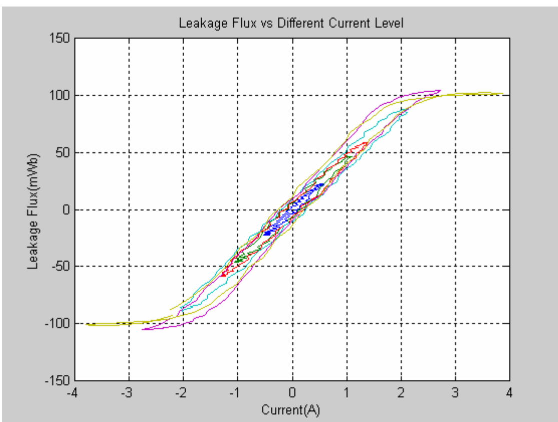


Figure 10. Leakage Flux linkage versus different current level

Figures 5–7 and 8-10 show self, mutual and leakage flux linkage characteristics versus against different input current and rotor positions respectively. Mutual flux linkage is half of self flux linkage which is also a half of leakage flux. The significant amount of leakage flux is constituted by the large amount of air gap.

Self 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 without significant flux saturation.

2.5 Modelling

An exponential flux model employed is shown as equation below [10]. Then a least square nonlinear two-dimensional surface fitting method is applied to the flux-current chart so that the non-linear function λ can be represented by the following equation:

$$\lambda(\theta, i) = \lambda_s (1 - e^{-f(\theta)i}) \qquad (7)$$

where $f(\theta) = a + b\cos\theta + c\cos 2\theta + d\sin\theta + e\sin 2\theta$, θ is rotor angle and λ_s is a constant, of which the magnitude is equal or greater than the saturation flux of the motor.

Figure 11 shows the 3D flux linkage profile, which is constructed by minimizing the sum-square error of its norm.

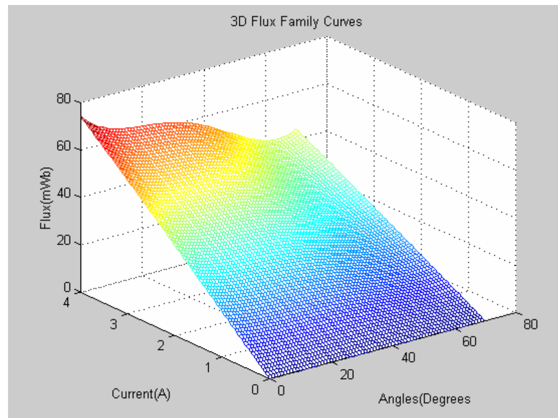


Fig. 11. 3D-Flux linkage profile of VR Gripper

Figure 12 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.

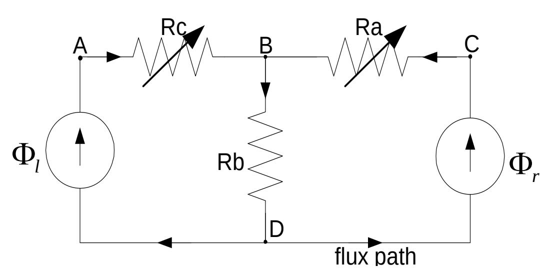


Figure 12. Equivalent VR Gripper magnetic circuit representation

Thus, the motor force model can be expressed as Equation (8) below.

$$F = \frac{1}{2l} i\lambda \sin(2\theta) \qquad (8)$$

where F, i, L, l and θ are rotor force, excitation current, self inductance, finger length and rotor angle [11].

Besides, with the experimental data obtained previously, force profile can be constructed from Equation (8) as shown in Figure 13.

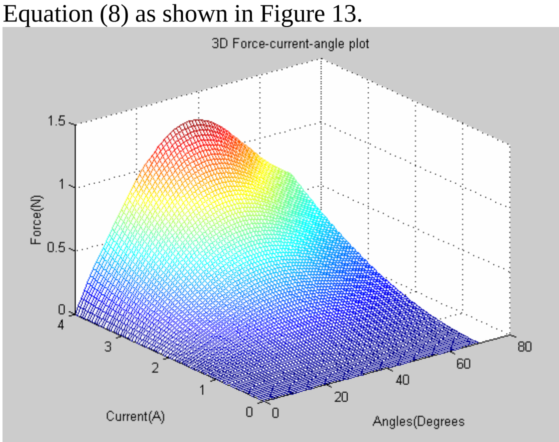


Fig. 13. 3D Force profile of VR Gripper

2.6 Force Profile Verification

The force model is verified with static force measurement. In Figure 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.

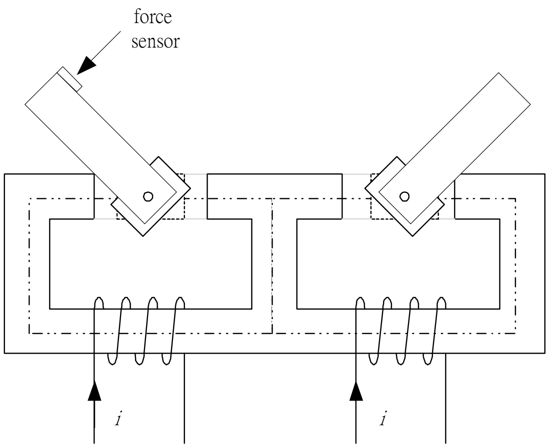


Figure 14. Force Model Verification Setup

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

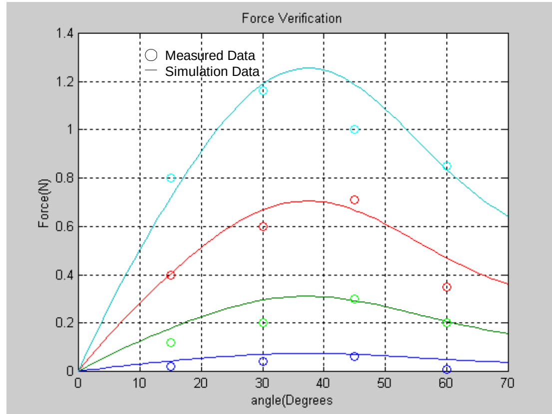


Fig. 15. Force Model Verification

3 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.

Flux linkages are measured and 3D-flux linkage profiles are generated with an exponential function surface fitting. The actuator inherits a non-uniform force profile as a reluctance actuator. 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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