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# Characterization of a novel two-finger variable reluctance gripper

Kenneth K. C. Chan, Norbert C. Cheung

*Department of Electrical Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

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**Abstract**

Variable reluctance (VR) actuator has a simple and robust structure. Without any 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 processors and power electronic drives in recent years, advance modeling techniques and control solutions can be realized onto VR actuators applications. For these reasons, 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 has been proposed and fabricated. Characterization measurements of the VR gripper were carried out. Measurement results show that the proposed actuator exhibits general characteristics as VR actuators and becomes more efficient through making use of mutual coupling. © 2005 ISA—The Instrumentation, Systems, and Automation Society.

*Keywords:* Variable reluctance; Gripper; Flux characterization

## 1. Introduction

Force control of robotic gripping has been the subject of numerous robotic researchers. Numerous grippers were designed for specific force control applications, employing various types of actuators, namely, dc motors, PZT, thermal and pneumatic actuators. However, the use of variable reluctance (VR) technology remains unexplored.

Each of the above-mentioned actuators has its own shortcomings. Thermal grippers suffer from slow force responses and small opening areas [1]. Pneumatic grippers are commonly found in high force applications but inherit slow force responses like thermal actuators [2]. Voice coil or dc motors can be an alternative solution [3]. However, with permanent magnet (PM), actuators tend to be costly. Piezoelectric grippers tend to provide highly accurate force but their displacement is small, and their force output is low [4]. On the contrary, the VR actuator enjoys very few mechanical components, fast force response, and high-precision in position and force control.

The VR actuator has a simple and robust structure. With the absence of PM, it tends to have a lower inertia and a wide operating temperature. The stator windings are easy to fabricate, for these reasons, the actuator has a very low manufacturing cost. However, it also suffers from its own disadvantages. The VR actuator inherits nonlinear torque properties and thus increases its control complexity [5]. As a result, controlling the VR actuator as a proportional device is the most difficult obstacle to gaining popularity. With the advancement of semiconductor components, the cost of implementing an advance modeling method and control strategies has become affordable. Industrial applications of VR actuators have emerged.

The main objective of the project is to design and fabricate a novel two-finger VR gripper. Efficiency is also increased by combining the two individual magnetic circuits. This paper presents a

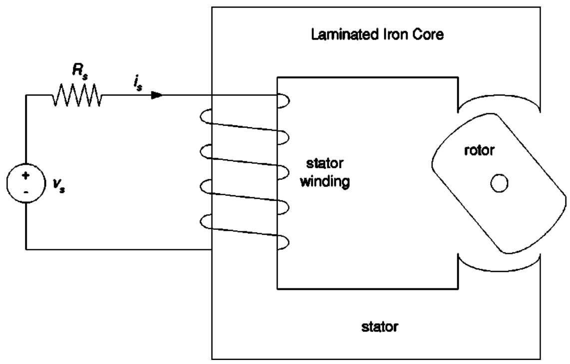


Fig. 1. A rotating VR motor.

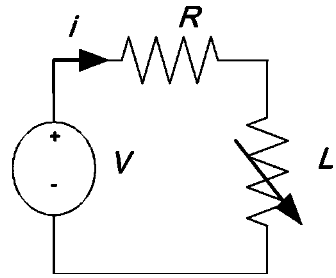


Fig. 2. Electric circuit of a rotating VR motor.

novel mutually coupled two-finger gripper suitable for position and force control applications. The gripper is unique for the employment of VR technology. This paper describes the design analysis in Section II. Section III shows the construction of the proposed VR finger gripper. An appropriate and accurate flux measurement experimental setup is presented in Section IV. Experimental results show in Section V state that the efficiency of the proposed VR finger gripper is raised with the use of mutual coupling.

## 2. Design and analysis

Fig. 1 shows a rotating VR motor [6]. It mainly consists of a rotor, a stator winding, and an iron core to link up the magnetic circuit. When a current $i_s$ passes through the stator winding, then magnetic flux links through the iron core and eventually the rotor will be attracted into the alignment with the pole pieces. On the contrary, if an external restraining torque is applied to the rotor and displaced from the aligned position, the rotor will stay in an equilibrium position where the rotor alignment torque balances out the external restraining torque.

The iron core is usually laminated to reduce the eddy current effect. Without PM, 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.

The operating principle of a VR motor is similar to a solenoid; it has higher inductance and slower current response than PM motor. Furthermore, VR actuator inherits nonlinear properties and thus increases its control complexity. As a result, the use of VR technology in gripper application is never explored.

An ideal gripper should have a fast force response, high efficiency, and robustness. It should also be low in cost. The main aim of this project is to develop a novel two-finger gripper using VR technology taking advantage of its high-torque efficiency, robust characteristics, and construction simplicity. This project also explores its potentials on high-precision applications, which is seldom used due to its nonlinear magnetic characteristic and force profile. The work achieved here would be the first of its kind to design and develop a high-speed and high-precision robotic gripper using VR technology.

Fig. 2 shows the electric circuit of a rotating VR motor. The VR motor can be represented as a resistive and a variable inductive structure. Its voltage equation can be expressed as

$$V = Ri + \frac{d\lambda(\theta,i)}{dt} = Ri + \frac{d\lambda_s}{dt} + \frac{d\lambda_m}{dt} + \frac{d\lambda_l}{dt}, \tag{1}$$

where $V$, $R$, $i$, $\theta$, $\lambda$, $\lambda_s$, $\lambda_m$, and $\lambda_l$ represent terminal voltage, coil resistance, current, rotor angle, total flux linkage, self-, mutual, and leakage flux linkage, respectively [7].

Magnetization curves shown in Figs. 3(a) and (b) are curves of flux linkage $\lambda$ versus current $i$, at a particular position for a linear and saturated magnetic device. Torque produced, $T$, can also be represented as

$$T = \left[\frac{\partial W_c}{\partial \theta}\right]_{i = cons\tan t},$$

$$W_c = \int \lambda \, di. \tag{2}$$

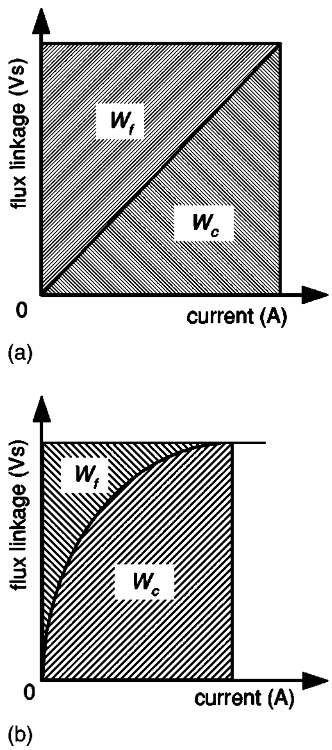


Fig. 3. (a) Magnetization curve of a linear device. (b) Magnetization curve of a saturated device.

From Eq. (2), it can be clearly seen that shaded area of co-energy, $W_c$, determines torque production. For the VR motor, it becomes more efficient once it enters the saturation region. Hence it is a common practice to increase the stator current for a higher torque production. This project aims at designing a two-finger VR gripper which drives the motor to saturation region at a lower current level than an ordinary VR actuator.

It is important to notice that there is a limited stroke for the VR finger gripper and therefore it prevents the rotor from achieving extremely high speed. As a result, Eq. (2) can be approximated as

$$T \approx i \frac{\partial \lambda}{\partial \theta}. \tag{3}$$

An exponential flux model employed is shown as Eq. (4) below [8]. Then a least-square nonlinear two-dimensional surface fitting method is applied to the flux-current chart so that the nonlinear function λ can be represented as

$$\lambda(\theta,i) = \lambda_{sat}(1 - e^{-f(\theta)i}),$$

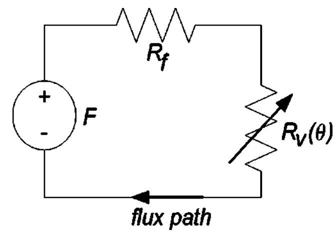


Fig. 4. Equivalent magnetic circuit of a rotating VR motor.

$$f(\theta) = a + b\cos\theta + c\cos 2\theta + d\sin\theta + e\sin 2\theta, \tag{4}$$

where $\theta$ is the rotor angle and $\lambda_{sat}$ is a constant, with magnitude $\geqslant$ the saturation flux.

A magnetic system can be represented by an equivalent magnetic circuit [9]. By applying basic electric circuit theories, analyzing a magnetic circuit would be equivalent as an electric circuit. This becomes a major main advantage of transforming a magnetic system to its equivalent magnetic circuit. Nevertheless, once the motor enters saturation region, analyzing with equivalent magnetic circuit is no longer valid, however, the flux path links in the same manner whether the VR gripper operates in either linear or saturation region.

In a magnetic circuit, stator winding, stator, and rotor reluctances can be represented by magnetomotive force (MMF) source, $F$ and fixed reluctance, $R_f$ and variable reluctance, $R_v$. Fig. 4 shows the equivalent magnetic circuit of a rotating VR motor.

To design a two-finger VR gripper, the simplest method is to allow each finger driven by an individual actuator. Fig. 5 shows the equivalent magnetic circuit of a finger gripper driven by two individual VR actuators. The stator windings, rotor, and stator core can be represented by MMF sources, $F_{left}$ and $F_{right}$, variable reluctance, $R_a$,

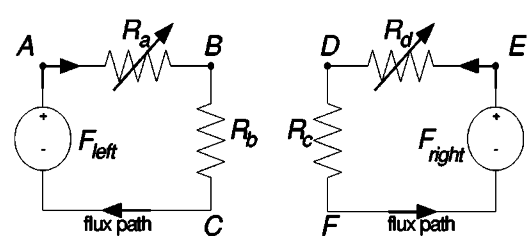


Fig. 5. Equivalent magnetic circuit of the two-finger VR gripper without magnetic coupling.

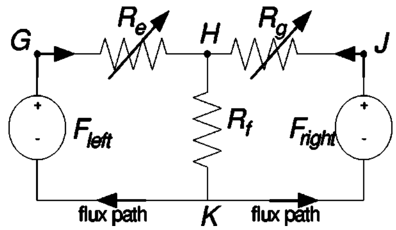


Fig. 6. Equivalent magnetic circuit of the two-finger VR gripper with magnetic coupling.

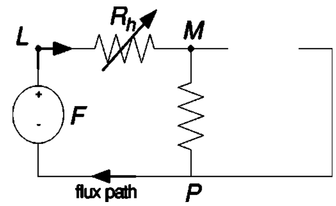


Fig. 7. Equivalent magnetic circuit of the two-finger VR gripper with only one rotor being installed.

$R_d$, and fixed reluctance $R_b$, $R_c$. The left and right magnetic circuit link through path ABC and DEF, respectively, without any mutual flux coupling. Due to the symmetrical structure of the actuator, the excitation currents in gripping motion can be considered equal and the variable and fixed reluctances can be assumed equivalent on the two magnetic circuits. In other words, $F_{left}$ is equal to $F_{right}$; $R_a$ is equal to $R_d$; $R_b$ is equal to $R_c$.

Generally, engineers are used to avoid mutual flux coupling between phases. It does not only hinder motor torque production but it also increases model complexity. In this project, the two magnetic circuits are connected with a common flux return path.

Fig. 6 shows the equivalent magnetic circuit of the two-finger VR gripper proposed for this project. Similarly, the stator windings, rotor and $E$ core can be represented by MMF sources, $F_{left}$ and $F_{right}$, variable reluctance, $R_e$ and $R_g$, and fixed reluctance $R_f$ with $F_{left}$ being equal to $F_{right}$; $R_e$ being equal to $R_g$. It can be considered as two individual rotating VR motors being combined together. Besides, return paths of both magnetic circuits are connected together with nodes H and K. Therefore no mutual flux coupling would be detected because there is no any potential difference. Furthermore, by linking the two return paths together, the magnetic circuit can be saturated easier with two MMF sources. In other words, the VR gripper can enter the saturation region at a lower current level and thus increase its efficiency.

Fig. 7 shows the equivalent magnetic circuit of the two-finger VR gripper with one rotor being removed and one stator winding being excited. With one rotor being removed, it can be assumed that the flux link through path LMP and such setup can be assumed to be equivalent as an ordinary VR motor shown in Fig. 4.

## 3. Construction of the VR finger gripper

Fig. 8 shows the construction of the two-finger VR gripper used in this research project. Figs. 8(a) and (b) show its grasps and release positions, respectively. As mentioned in previous section, it is made up of two basic rotating VR motors. The overall construction is extremely simple and robust, and it is very similar to the rotating VR motor mentioned previously. Combining the two fingers into a single magnetic housing has made the finger alignment process much simpler and the overall size much smaller. Fig. 9 shows the basic construction of the project two-finger VR gripper. It consists of two rotary elements, each attached to a finger. The actuator contains two coils with 400 turn windings each. Both the rotors and stators are made up of laminated mild steel to reduce eddy current effects.

The moving rotors are mounted onto two individual shafts, whose axes are normal to the plane of the stator, so that it can rotate freely between the poles of the stator. Each rotor shaft is supported by a pair of bearings with an incremental encoder resolution of 0.09°, mounted onto the shaft for position sensing. Two detachable fingers of the gripper are 90 mm long and spring loaded, which allows bidirectional movement from single direction excitation of the coils. They can also be redesigned to adapt any kind of gripping object.

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 70°, the fingertips would be closed and the rotors are in fully grasp positions. Specification of the project VR gripper is tabulated as Table 1.

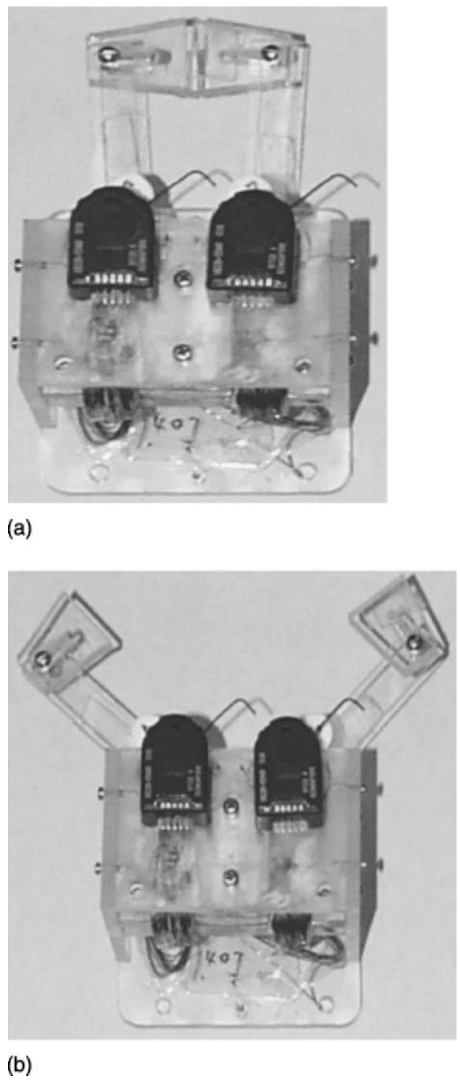


Fig. 8. (a) Project two-finger VR gripper at aligned position. (b) Project two-finger VR gripper at release position.

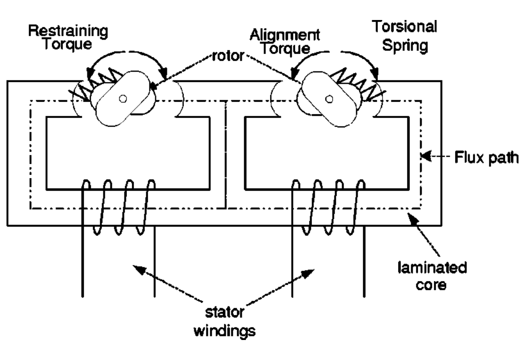


Fig. 9. Construction of the project two-finger VR gripper.

Table 1
Specifications of the two-finger VR gripper used in the project.

| | |
|---|---|
| Make | Department of Electrical Engineering, The Hong Kong Polytechnic University |
| Type | Two-finger VR gripper |
| Stroke angle | 70 degrees |
| Operating voltage | 40VDC |
| Maximum current | 4A |
| Resistance | 4Ω |
| Inductance | 29.1 mH–41.7 mH |
| No. of turns per coil | 400 turns |

## 4. Measurement and verification

In order to prove the design mentioned, flux linkage and motor torque must be measured. However, for VR finger gripper, flux linkage measurement requires special technique. In recent years, numerous researchers have developed various methods for flux linkage measurement on VR motors. A direct measurement method was developed which requires an elaborate hardware. As a result, hardware components affect measurement accuracy through sensitivity, temperature drifting, and cost [10]. Indirect measurement method was then developed which is comparatively simpler and requires fewer hardware circuitry. However, it measures the voltage across the motor winding. Without any voltage regulation; the experiment introduces extra measurement error [11]. It was later improved by using a lead acid battery for removing the voltage source and current ripple [12].

The most appropriate flux linkage measurement method is the ac excitation method which has been mentioned in Refs. [13,14]. Search coils are placed at strategic points of the magnetic circuit. When a flux passes through a search coil with $N_s$ turns, an electromotive force (EMF), $e(t)$, would be induced and thus flux $\Phi(t)$ can be expressed as

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

In the flux measurement, both rotors are locked at the same angle. Both motor windings are connected in series and therefore excited with same current levels at 50-Hz ac current which can be easily produced with an isolated autotransformer. Rotors are fixed at same angles. Current is measured from a low impedance resistor.

Since calculation of flux is an integration process, a slight dc offset in the integration process will produce a significant shift in the integrated value over a prolonged period. To eliminate this error, a compensation value of $\delta e$ is added to the integration process, as

$$\delta e = \frac{\int_0^T e(t) - e(0)}{N_{samples}}, \tag{6}$$

where $T$ is the period of the input ac current, $e(0)$ is the initial measured voltage across the search coil, and $N_{samples}$ is the number of samples during one period $T$.

Besides, since the input ac current and voltage across the stator winding are symmetrical with zero mean values, so the flux output can also be assumed to be symmetrical with zero mean value. In other words, the flux signal, $\Phi(t)$ should have the same maximum and minimum values. As a result, the initial flux, $\Phi(0)$, having the effect of shifting $\Phi(t)$ to a symmetrical position, can be obtained as

$$\Phi(0) = \frac{\Phi(2) - \Phi(1)}{2}. \tag{7}$$

Combining Eqs. (8) and (9), Eq. (7) can be rearranged as

$$\Phi(t) = -\frac{1}{N_s}\int_0^t [e(t) + \delta e]dt + \Phi(0). \tag{8}$$

A dSPACE DS1104 card is used as the data acquisition controller. The card has an on-board 250-MHz PowerPC 903e core processor for real-time computation and it interfaces with the PC through the PCI bus. It consists of two 24 bits incremental encoder input channels, eight ADC and seven PWM channels. In connecting with MATLAB real-time workshop and SIMULINK, real-time control C-code can be generated with a SIMULINK diagram. Assembly codes can be compiled and downloaded to the microprocessor.

Different voltages induced from the search coils and stator current levels are filtered, amplified, and are fed into the ADC channels. Encoders are also connected to the measurement system to provide high precision position information. The overall experimental setup is shown in Fig. 10.

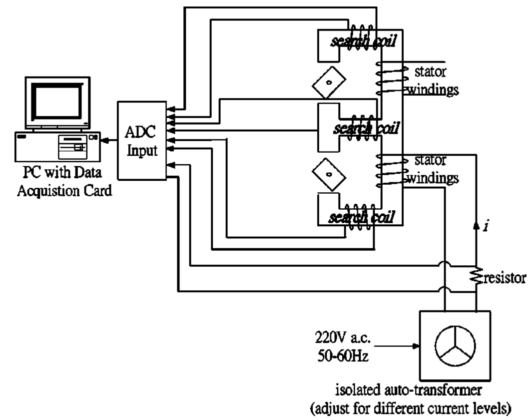


Fig. 10. Experimental setup for flux linkage characterization.

Flux linkage is measured with stator current ranging from 0.5 to 4 A and angular position ranges from 0° to 70° with two sets of flux linkage results being recorded. One is measured with only one stator winding being excited with only one rotor being installed with equivalent magnetic circuit shown in Fig. 7. This can be assumed to be simulating the effect of the finger driven by an ordinary VR motor without any magnetic coupling effect. The other set of results were recorded with both stator windings connected in series and being excited at the same current level and rotors being locked at same angular positions. Its corresponding equivalent magnetic circuit is shown in Fig. 6. Such setup represents the actual performance of the VR finger gripper with magnetic coupled effect.

Besides, direct torque measurement is a direct and effective way to determine the torque production efficiency of the VR motor. A torque gauge is mounted along the rotor shaft as shown in Fig. 11. Current, ranging from 0.5 to 4.0 A, is applied into both stator windings with a variable power supply. Torque is measured at different current levels and rotor angles, from fully opened to fully closed positions, for both magnetic coupled and noncoupled effect.

## 5. Results

Fig. 12 shows flux linkage measurement for the coupled VR finger gripper. Fig. 13 shows the non-

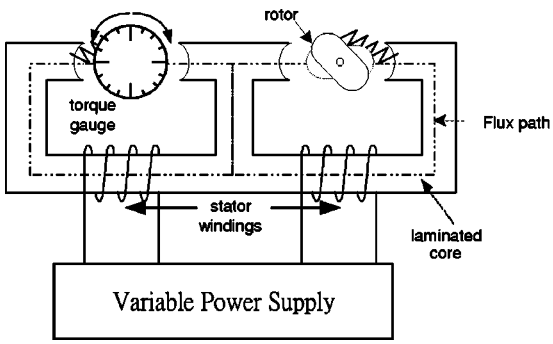


Fig. 11. Direct torque measurement setup.

coupled result. The coupled VR finger enters the saturation region at around 2 A whereas the non-coupled version does not enter saturation until the stator current reaches 3 A. It is clear that the coupled VR finger gripper enters saturation at a lower current level compared with the noncoupled one. As clearly mentioned earlier, it is more efficient for the VR motor to operate in a saturated region than in a linear region. In other words, it can be said that the coupled VR finger gripper is more efficient compared with the noncoupled one.

With the flux measured, the motor torque can then be calculated and compared with the actual torque measured. Figs. 14 and 15 show the direct torque measurement and simulated torque values for coupled and noncoupled VR finger grippers, respectively. It is clear that the torque produced by the coupled VR finger gripper is higher than for

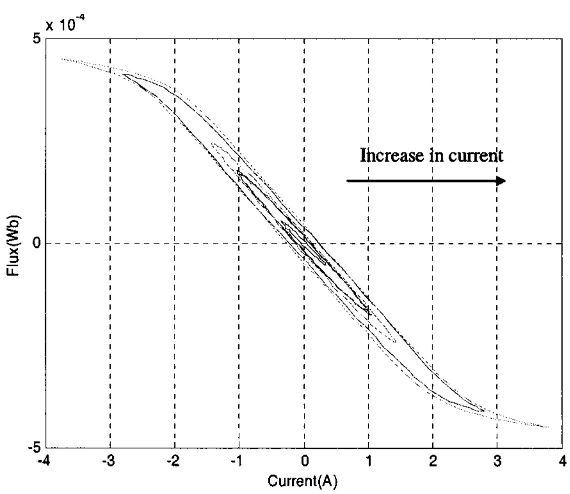


Fig. 12. Flux linkage measurement for coupled VR finger gripper.

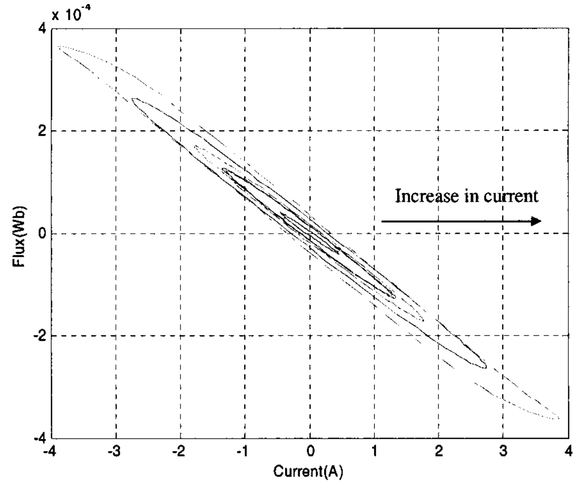


Fig. 13. Flux linkage measurement for noncoupled VR finger gripper.

the noncoupled one. The difference is more serious when the rotor angle is 35°. It is because the rotor pole tips have just overlapped with the stator pole tips and they become heavily saturated. This sudden change of flux introduces a high torque generation. Once again, above-mentioned results clearly show that the coupled VR finger gripper is more efficient. There are some slight discrepancies between the simulated and measured torque which can be explained by the presence of unmodeled leakage flux and frictional torque.

## 6. Conclusion

Gripping force control has always been an important research area. It also draws numerous in-

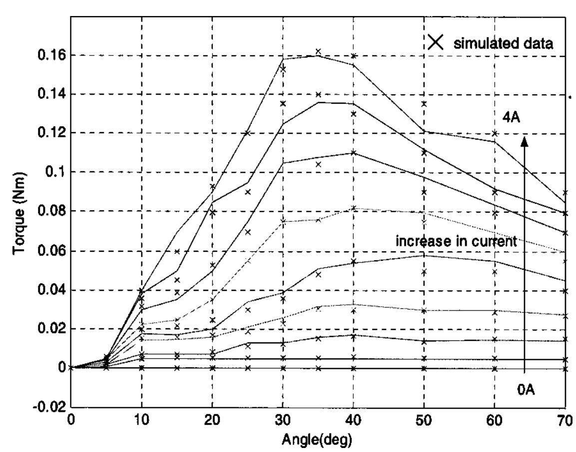


Fig. 14. Direct torque measurement for coupled VR finger gripper.

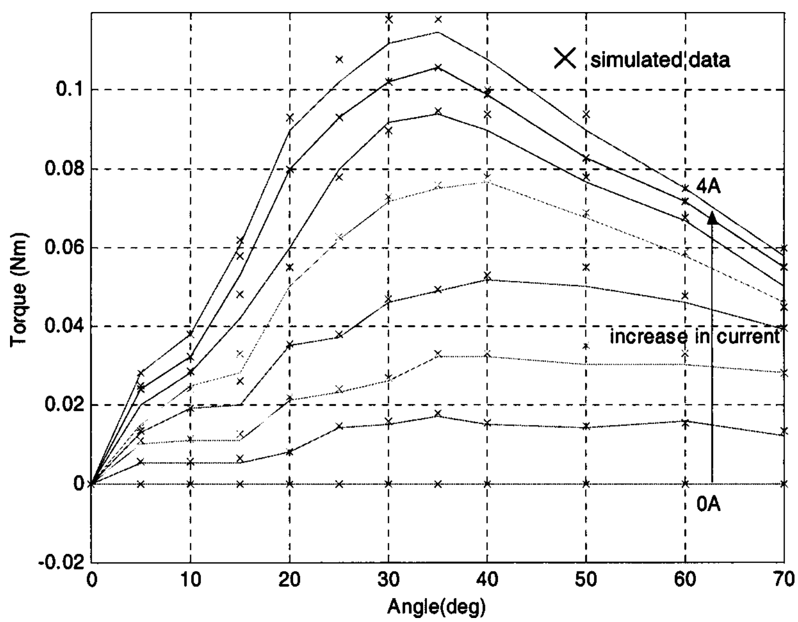


Fig. 15. Direct torque measurement for noncoupled VR finger gripper.

dustrial attentions due to its important role in the manufacturing industry. Various kinds of robotic grippers are designed for customized applications.

The VR actuator has a simple and robust structure. It has few components and thus has a very low manufacturing cost. This in turn tends to have a higher reliability. With proper stator winding selection, the VR motor can operate at an extremely high operating temperature range. However, the VR actuator inherits nonlinear properties and thus increases its control complexity. This hinders the industrial application on robotic gripping.

In this paper, a first of the kind coupled VR finger gripper has been carefully designed and fabricated. The main objective of the project is to design and fabricate a novel two-finger VR gripper, which has a higher efficiency by combining the two magnetic circuits. This paper describes the design analysis and the construction of the proposed VR finger gripper. Flux linkage characterization and direct torque measurement were carried out to prove the effectiveness of the VR finger gripper. With the results obtained, it clearly shows that the VR finger gripper exhibits similar characteristics as a general VR motor but with better efficiency. This VR finger gripper is appropriate to serve as an alterative high-precision industrial force gripping solution.

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**Kenneth K. C. Chan** obtained his B.Sc. in Electrical Engineering from the University of New South Wales in 1997. He is presently undertaking a Ph.D. study in variable reluctance gripper in the Department of Electrical Engineering of Hong Kong Polytechnic University.

**Norbert C. Cheung** obtained his B.Sc., M.Sc., and Ph.D. from the University of London, University of Hong Kong, and University of New South Wales in 1981, 1987, and 1995, respectively. His research interests are motion control, actuators design, and power electronic drives. He is now a lecturer in the Department of Electrical Engineering of the Hong Kong Polytechnic University.