A Polymer-Based Air Gap Length Prediction Method With Current Injection and Fuzzy Logic Observer

Yu Zou[1,2], K. W. Eric Cheng[2], Norbert C. Cheung[2], and J. F. Pan[1]

[1]Laboratory of Space Collaborative Manipulation Technology, Shenzhen University, Shenzhen 518060, China
[2]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong

In this paper, an approach combining current pulses injection and fuzzy logic observer to measure the air gap length of linear machines is proposed. A polymer enclosed by a coil is produced and selected as the test object. The characteristics and production process for the polymer is introduced and its magnetic feature has been studied. Injecting current pulses is used to calculate the self-inductance of the coil fixed on the cores that is directly influenced by the air gap length from the polymer. By using a fuzzy logic observer, the air gap length can be estimated precisely according to the variations of the self-inductance. Experimental results show the effectiveness of the proposed measurement method and the results prove that the proposed method is suitable for the air gap measurement for linear machines.

Index Terms—**Air gap length, current pulse injection, fuzzy logic observer, polymer.**

I. INTRODUCTION

FOR electric machines, especially permanent magnet machines, switched reluctance machines, and electric transformers, air gaps are dominant factors that affect the performance of the machines, since the air gap lengths directly influence the magnetic paths. Controllers can regulate the machine performance via feedback ways, including phase currents, position, and velocity signals, to compensate the mechanical outputs due to variations of air gap lengths between rotors/movers and stators. In [1]–[3], applying an auxiliary coil fixed on a ferromagnetic core is introduced to measure air gap lengths. However, nonlinear characteristics of the ferromagnetic cores deteriorate the accuracy of the measurement and the overall performance of the machines. Due to linear magnetized features, polymer bonded magnetic materials are much easier to obtain a precise value of the air gap length and these materials offer significant advantages over conventional materials such as easy molding and low cost [4]. Importantly, there are no eddy currents passing through the polymers owing to their low conductivities. Among several measurement methods, the pulse injection approach is a popular one in recent research [5]. Therefore, polymer bonded material is a potential method to estimate air gap lengths of machines by injecting high-frequency current into coils. In addition, the fuzzy logic algorithm has the characteristics of more robustness and easy implementation and it has become more and more popular in the controllers for electric machine systems. In [6], fuzzy log modeling of switched reluctance machines has been investigated to improve the performance of the machines. A torque ripple reduction scheme based on the fuzzy logic method is developed for switched reluctance machines [7]. Moreover, a fuzzy logic controller is also employed to reduce torque ripples and regulate the speed of permanent magnet machines [8], [9].

In this paper, an approach to evaluate the air gap length of linear machines by employing a polymer bonded magnetic material and using a fuzzy logic observer is proposed. Based on the polymer material, current pulse injection and fuzzy logic observer are employed simultaneously to achieve a high precision prediction for the air gap length. The current pulse injection method is considerably suitable for the air gap test with low joule losses and the fuzzy logic observer can avoid the disturbance from white noise.

The innovation of this paper includes the following. The attempt of the air gap length measurement of linear machines based on polymer bonded materials is first carried out. The fuzzy logic observer is employed to estimate the self-inductance for a better precision. Experimental results prove that the maximum error falls into 0.003 mm of precision, when the detected air gap length 0–2 mm.

II. MATERIAL PREPARATION AND CHARACTERISTICS

To produce the polymer bonded magnetic material, appropriate amounts of alpha-Fe_2O_3, NiO, and ZnO are mixed in a high-speed blender. After fully blended, the mixture is then sintered in a high-temperature calcination furnace and the material is heated gradually, with the temperature grows from room temperature to 1300 °C. The increase in speed of the temperature is 8 °C/min. The next step is to cool down the melted mixture after getting it out from the furnace and immersing it into an environment of room temperature so that the temperature of the mixture can drop rapidly. Finally, polymer blocks with the thickness of 3 mm can be obtained by dividing the cold mixture [4]. The photograph for the material is shown in Fig. 1(a). The measured hysteresis (B–H curve) loop of the polymer material is shown in Fig. 2(b). It is clear that the hysteresis loop is narrow, which indicates low hysteresis loss of the material when excited by high-frequency currents. Meanwhile, the B–H curve is almost a linear line that can avoid nonlinear magnetic characteristics [5]. It is also

Manuscript received March 9, 2017; revised May 17, 2017; accepted May 18, 2017. Date of publication May 23, 2017; date of current version October 24, 2017. Corresponding author: J. F. Pan (e-mail: pan_jian_fei@163.com).

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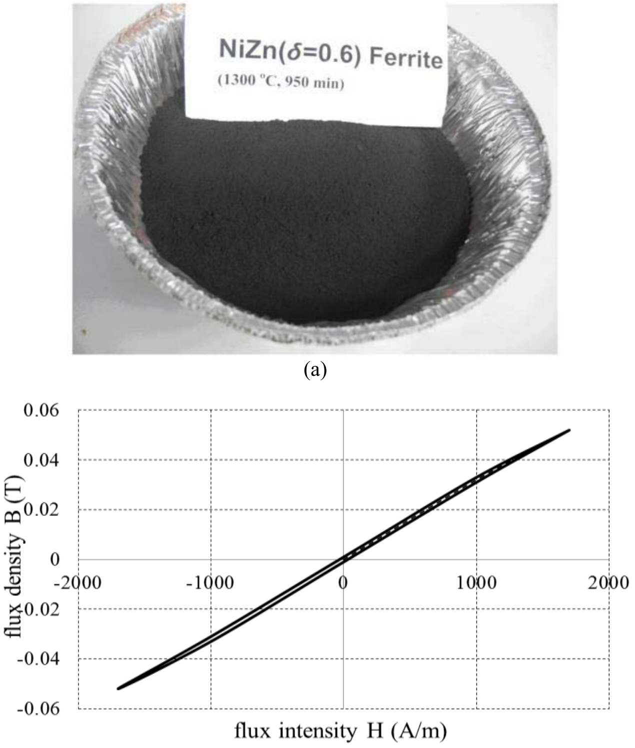
Digital Object Identifier 10.1109/TMAG.2017.2707072



(a)

(b)

Fig. 1. (a) Photograph of the polymer material. (b) Measured B–H loop.

TABLE I
MAJOR MACHINE SPECIFICATIONS

Parameter (symbol)	Value
E core width (w)	40 mm
E core height (h)	20 mm
Height of winding slot (p)	15 mm
Middle pole radium (m)	10 mm
Width of winding slot (n)	10 mm
I core height (t)	3×4.5×40 mm^3
No. of turns of the coil	160
Phase resistance	1.0 Ω

beneficial for the fuzzy logic observer to map the current value with respect to the change of the air gap.

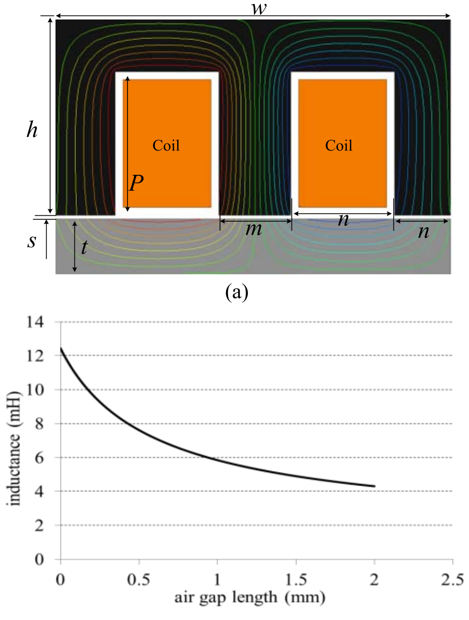
The test object and its flux line path are shown in Fig. 2(a). It is a typical EI core structure and the major specifications are listed in Table I. By injecting high-frequency current pulses, a coil fixed on the E core is used to calculate the air gap length between E core and I core. The self-inductance profile is shown in Fig. 2(b).

III. THEORETICAL BACKGROUND

A. Current Injection

The imposed current pulses are employed without the introduction of any extra hardware. By injecting the high-frequency current pulses of 10 kHz into the un-energized phase, the information of the air gap can be indirectly calculated according to the measurement of the current signal [6]. The basic equation can be expressed as follows:

$$u = Ri + \frac{d\lambda(i,s)}{dt} = Ri + L\frac{di}{dt} + i\frac{\partial L}{\partial i}\frac{di}{dt} + i\frac{\partial L}{\partial s}\frac{ds}{dt} \qquad (1)$$



(a)

(b)

Fig. 2. (a) Structure of the EI core. (b) Self-inductance profile.

where u, R, i, and L are phase excitation voltage, resistance, current, and self-inductance, respectively. λ and s are flux linkage and length of the air gap. L can be regarded as a constant value since the influence of the current pulses and the length of the air gap of the core in a very short time can be neglected [7]. The voltage balance equation can further be formulated as

$$u = Ri + L\frac{di}{dt}. \qquad (2)$$

Therefore, the value of the current can be obtained by solving the following equation:

$$i = \frac{b}{a} \times u \times (1 - e^{-\mathrm{at}}) \qquad (3)$$

where $a = R/L$ and $b = 1/L$. The injected current pulses of the coil are shown in Fig. 3.

B. Fuzzy Logic Observer

A fuzzy logic observer mainly includes the fuzzification, rule base design and de-fuzzification process. A current sensor is used to feedback the current signal of the coil. Its self-inductance can be calculated through the current feedback and the change rate of current. After obtaining the phase inductance of the test object, the values of phase inductance and its derivatives are supplied to the fuzzy logic observer as input variables. The calculation process employs the fuzzy logic rule according to the function of the phase inductance and the air gap length between the I-core and the E-core. A training scheme is first applied to create a fuzzy rule based on the measured data from the test object. After training, the fuzzy logic rule base defines the nonlinear multi-input-single-out function which translates inputs of phase inductance and its derivatives into output values of the airgap length.

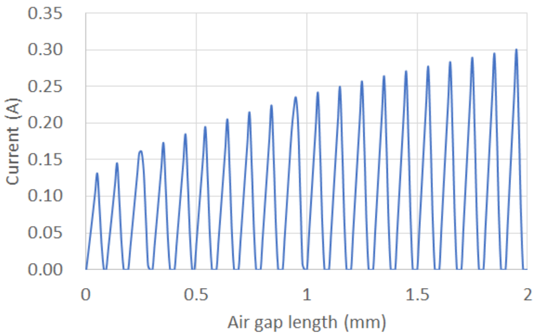


Fig. 3. Injected current pulses in the test coil.

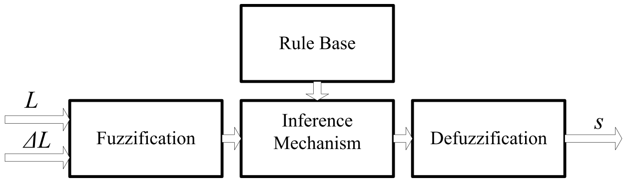


Fig. 4. Fuzzy logic observer block scheme.

TABLE II

RULE BASE OF THE OBSERVER

L \ ΔL	NB	NM	NS	ZO	PS	PM	PB
SS	PB	PB	PM	PM	PS	ZO	ZO
LS	PB	PB	PM	PS	PS	ZO	NS
S	PM	PM	PM	PS	ZO	NS	NS
M	PM	PM	PS	ZO	NS	NM	NM
L	PS	PS	ZO	NS	NS	NM	NM
XL	PS	ZO	NS	NM	NM	NM	NB
XXL	ZO	ZO	NM	NM	NM	NB	NB

The entire block diagram of the fuzzy logic observer is shown in Fig. 4.

The function can thus be formulated as

$$f(L, \Delta L) \rightarrow s \tag{4}$$

where L and ΔL are values of the phase self-inductance and its derivative, respectively.

In order to obtain a low steady state error, Mamdani type of fuzzy logic observer is employed. The fuzzy sets of ΔL are defined as: negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), position MEDIUM (PM), and positive big (PB). The inductance L can be distributed by the following fuzzy sets: super small (SS), large small (LS), small (S), medium (M), large (L), extra-large (XL), and (XXL).

Fig. 5(a) shows the membership function of the fuzzy logic observer. Fig. 5(b) and (c) is the inputs and the output of the fuzzy logic observer. Table II lists the rule base of the fuzzy logic observer.

Defuzzification is introduced to translate the fuzzy reasoning results into clear values, and the Mamdani inference is selected as the fuzzy inference method [8]. It contains three processes: 1) the aggregation; 2) activation; and 3) accumulation of membership function. The area center of gravity method is adopted as the defuzzification strategy and it is denoted as

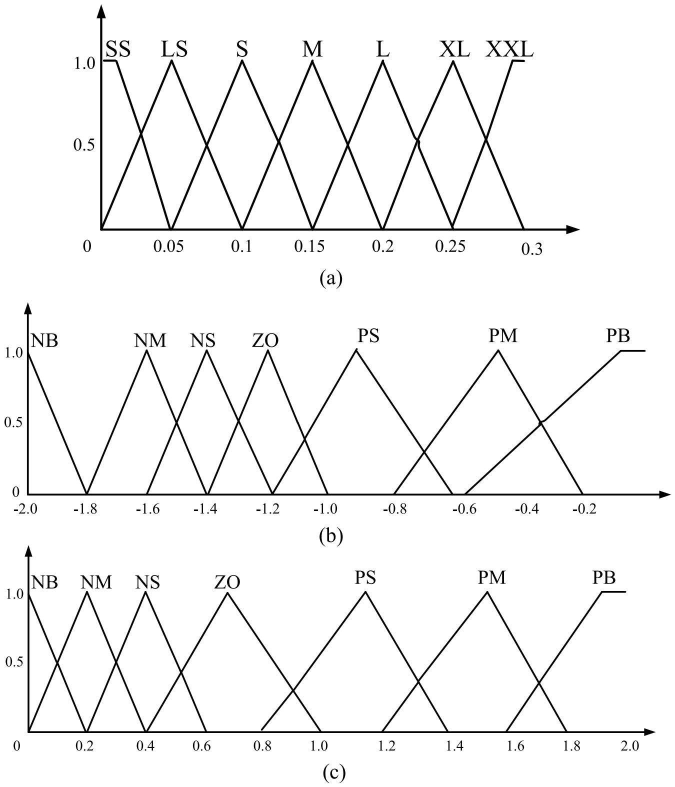


Fig. 5. (a) Membership functions. (b) Fuzzy logic inputs. (c) Outputs.

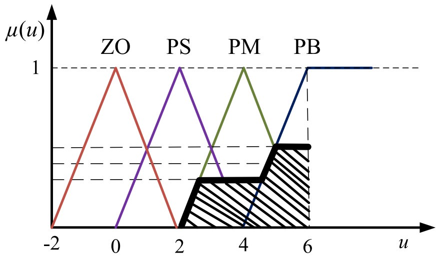


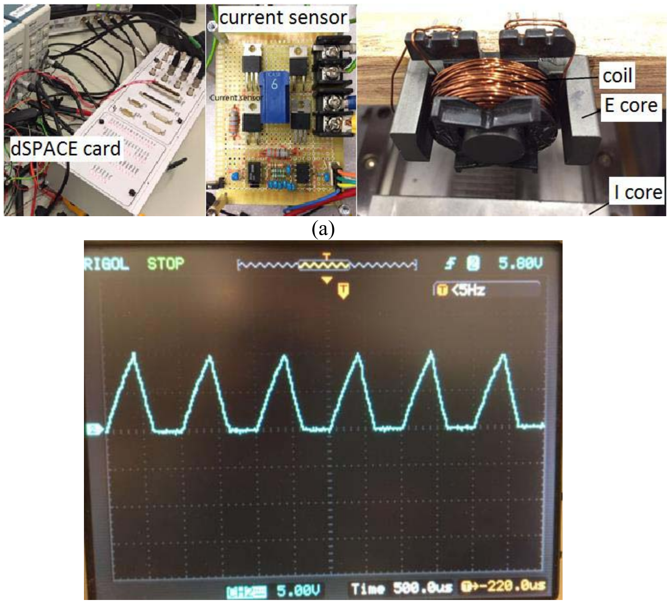
Fig. 6. Membership functions obtained from Mamdani inference.

$$u^* = \frac{\int_{\mathrm{MIN}}^{\mathrm{MAX}} u \cdot \mu(u) du}{\int_{\mathrm{MIN}}^{\mathrm{MAX}} \mu(u) du} \tag{5}$$

where u^* is the defuzzification output value and u is the independent variable of membership function domain. $\mu(u)$ is the membership function accumulated from Mamdani inference method as the black bold line shown in Fig. 6. [MIN, MAX] is the domain of the $\mu(u)$. The enclosed area by $\mu(u)$ polyline and u axis is the integral area which is shadowed in Fig. 6.

IV. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 7(a). It mainly includes the test object composed of the polymer wrapped by a coil. A half bridge convertor is employed to inject current pulses for the coil. The current signals are sampled by a *LEM* current sensor with the measurement error of 0.2%. Current signal is fedback to the dSPACE card DS1104 and the fuzzy



(a)

(b)

Fig. 7. (a) Experimental setup. (b) Measured current pulse (100 V/A).

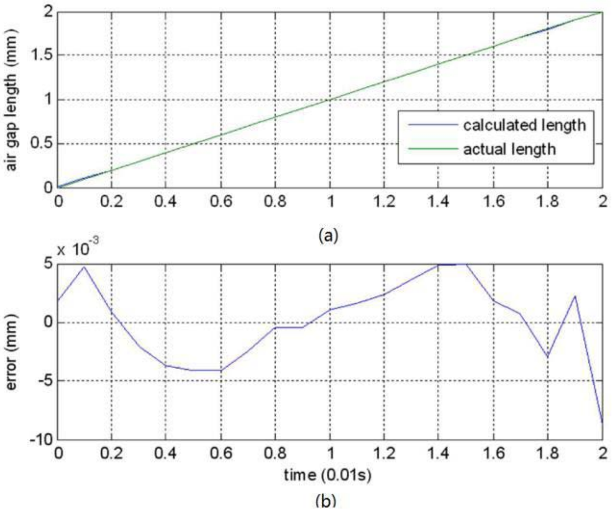


Fig. 8. (a) Estimated air gap length. (b) Dynamic error profile.

logic observer is implemented in Simulink software package directly. The magnetic force generated by the polymer core can be ignored since the amplitude of the current pulses is low. The core is fixed on a mover of a linear motor to control the air gap length of the core and the air gap length can be detected by a linear Renishaw optical grid position sensor with the resolution of 0.1 μm.

The coil is excited with the input voltage of 5 V when the linear machine translates at the speed of 0.1 m/s and. It can be seen that the peak current of each pulse goes up to 0.1 A when the air gap length is zero, as shown in Fig. 7(b).

The air gap length under test goes from 0 to 2 mm. According to the envelop curves of the current pulses, the fuzzy logic observer calculates the length of the air gap. The calculated length of air gap is shown in Fig. 8(a). The dynamic error profile is calculated by the difference of the actual values to those from the commercial linear sensor, as illustrated in Fig. 8(b). It can be seen that the maximum error falls into 0.003 mm of precision. The result suggests the effectiveness of the proposed method.

V. CONCLUSION

By using the current pulse injection method, the self-inductance of the coil that directly reflects the air gap length between the two polymer cores can be calculated. Experimental data show that the polymer possesses linear magnetized features and the fuzzy logic observer can estimate the air gap length correctly, compared to the measurement result from a linear position sensor. Experimental results prove the effectiveness of the measurement method for air gap lengths. It is expected that this approach can be used for air gap length detection of linear or rotary electric machines in industry.

The air gap measurement range for the polymer cores currently is 0–2 mm, which is suitable for common linear or rotary machines. For current polymers, the measurement accuracy will reduce for the detection of a large air gap length, due to the increased flux leakage. For larger air gap length measurement, it is suggested that the dimensions of the polymer cores are increased.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China under Grant 51477103 and in part by the Guangdong Natural Science Foundation under Grant S2014A030313564, Grant 2016KZDXM007, and Grant 2015A010106017. The authors would also like to thank Shenzhen Government for its support under code JCYJ20160308104825040.

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