Armature Reaction Field and Inductance of Coreless Moving-Coil Tubular Linear Machine

Liang Yan, Senior Member, IEEE, Lei Zhang, Zongxia Jiao, Hongjie Hu, Chin-Yin Chen, and I-Ming Chen, Fellow, IEEE

Abstract—Analysis of armature reaction field and inductance is extremely important for design and control implementation of electromagnetic machines. So far, most studies have focused on magnetic field generated by permanent-magnet (PM) poles, whereas less work has been done on armature reaction field. This paper proposes a novel analytical modeling method to predict the armature reaction field of a coreless PM tubular linear machine with dual Halbach array. Unlike conventional modeling approach, the proposed method formulates the armature reaction field for electromagnetic machines with finite length, so that the analytical modeling precision can be improved. In addition, winding inductance is also analytically formulated to facilitate dynamic motion control based on the reaction field solutions. Numerical result is subsequently obtained with finite-element method and employed to validate the derived analytical models. A research prototype with dual Halbach array and single phase input is developed. Experiments are conducted on the reaction field and inductance to further verify the obtained mathematical models.

Index Terms—Armature reaction, inductance, linear motor, magnetic field, permanent magnet (PM).

NOMENCLATURE

Φ Magnetic flux, Wb.

F Magnetomotive force (MMF), A.

l Half of the length of motor, m.

L, M Self-inductance and mutual inductance, H.

R Magnetic reluctance, Ω.

W Magnetic energy, J.

A Magnetic vector potential, Wb/m.

B Flux density vector, T.

H Magnetic field intensity vector, A/m.

J Current density vector, A/m².

τp, τr Pole pitch and axial width of radial magnets, m.

Br, Bz Radial and axial components of flux density, T.

I Current per turn, A.

k, Nk, p Number of positive coils, coil turns, and pole pairs.

ra, rb Outer and inner radii of internal permanent magnet (PM), m.

ri, ro Inner and outer radii of internal PM, m.

I. INTRODUCTION

Due to high power density, high efficiency, and compact structure, PM linear machines (PMLMs) have wide applications in transportation [1], [2], military [3], [4], and manufacturing [5], [6]. Systematic investigation on air-core PMLMs has been conducted by Boldea [7], Kremers et al. [8], Gysen et al. [9], and Wang et al. [10], [11]. Impressive work has been done on magnetic levitation systems and multi-degree-of-freedom actuators. Various approaches have been proposed to analyze magnetic field distribution of PM arrays [7], [12], [13]. An air-core tubular PMLM with new topology of magnet array, i.e., dual Halbach array, has been proposed to increase the force density and reduce the system vibration and noises [14], [15]. The magnetic flux density distribution of this electromagnetic machine caused by PM poles alone has been studied in detail [15]. However, armature is another important component that influences the system output significantly. When the machine is energized, the current in windings shifts and distorts the main flux, which is known as armature reaction [16]. The magnetic field on load is therefore a synthesis of PM field and armature reaction field. Although armature reaction field is relatively low, it may cause instability and tracking error, particularly for high-precision systems [17]–[19]. Therefore, it is important to analyze the armature reaction field precisely and, thus, to improve the control performance of PMLMs.

Analytical modeling based on harmonic expansion is generally an efficient method to study armature reaction [20]. It is more precise in the description of field distribution than conventional permeance models [21]–[23] and current sheet models [24]–[26]. It is also time saving and effective in design optimization of electromagnetic machines compared with finite-element method (FEM) [27]–[29]. Researchers have obtained analytical models of armature reaction fields on the premise of infinite length of electric motors. For example, Wang et al. presented accurate analytical expression of armature reaction field for a tubular PMLM with infinite length in [30]. Amara et al. derived the armature reaction field of a tubular PMLM by...
assuming infinite length of an electric linear machine [31], [32]. The assumption of infinite length of linear motor apparently simplifies the formulation procedure. However, it may also reduce the modeling precision and unavoidably influences subsequent system design and motion control implementation of electric machines.

Therefore, this paper proposes an analytical modeling method to describe magnetic field distribution of armature reaction in moving-coil PMTLMs by taking finite motor length into consideration. This method absorbs the merits of analytical model based on harmonic expansion and permeance model. The established model of armature reaction field is validated by FEM solutions and utilized to formulate winding inductance. It can benefit dynamic analysis and control of linear machines [31], [33]. A research prototype with dual Halbach array and single phase current is developed, and experiments are conducted on both armature reaction field and inductance to verify the developed analytical models. Along with the open-circuit analytical model, the proposed armature reaction field model can be employed for prediction of on-load field distribution of linear machines [34].

II. MACHINE STRUCTURE

The structure of a tubular PMLM with dual Halbach array is shown in Fig. 1. The major components include dual Halbach array, coreless winding, and inner and outer back irons. The radial magnets in different layers are magnetized in the same direction and the axial ones in the opposite direction. This magnet arrangement helps to increase the radial component of flux density in the air gap, whereas it reduces the axial component significantly. It indicates that the dual Halbach array may offer us two advantages, i.e., the axial force can be improved from the increased radial flux, and the radial force disturbance and vibration can be weakened from the decreased axial flux. A coreless winding is selected for the design to have a near-linear relationship between the current input and the force output, which may benefit real-time motion control of the system.

III. FORMULATION OF ARMATURE REACTION FIELD

A. Assumptions

- The magnetic permeability of back irons is infinitely large with respect to free space.

- Laminated irons are used, and thus, eddy currents in stator and mover are ignorable.

- The relative permeability of rare-earth PM is equal to that of free space.

- All materials are isotropic in terms of magnetic property.

B. Governing Equations

Based on Maxwell equation and under Coulomb gauge, the governing equation is derived as

\[ \nabla^2 \mathbf{A} = -\mu_0 \mu_r \mathbf{J}, \]

The machine space under study is separated into two types. Type 1 is the central part without hatched lines, as shown in Fig. 2, with the mover included; and type 2 is the part filled with horizontal hatched lines. Because only magnetic flux in the winding region affects the output performance of the linear machine, this section mainly focuses on the study of the central part. The hatched part will be employed for the study of inductance computation in subsequent section. The central part can be divided into two groups according to the current values. Specifically, Group 1 includes two layers of PMs and air gaps (Regions 1 and 3), and Group 2 is the current region (Region 2) with a single phase current input. The two groups are governed by Laplace’s and Poisson’s equations as follows:

\[ \nabla^2 \mathbf{A}_i = 0, \quad i = \{1, 3\}, \quad \nabla^2 \mathbf{A}_2 = -\mu_0 \mathbf{J}. \]
The transformation between CS2 and the CS1, as shown in Fig. 3. Its origin is at the geometry center of the cylindrical coordinate system CS1 is represented by

\[ z' = z + z_r \]

where \( z_r \) represents the mover position in CS1.

### D. Analytical Solutions of Magnetic Field

1) **Magnetic Field of Noncurrent Region**: Magnetic field of noncurrent region is the solution to the Laplace’s equation in (3). By taking variable separation, we assume that \( A_{i\theta}(r, z) = R(r)Z(z) \). Laplace’s equation is simplified to

\[
\frac{1}{z'(z)} \frac{\partial Z^2(z)}{\partial z^2} = k^2
\]

\[
r^2 \frac{\partial R^2(r)}{\partial r^2} + r \frac{\partial R(r)}{\partial r} + (k^2 r^2 - 1) R(r) = 0
\]

where \( k^2 \) is an eigenvalue. The general solution is

\[
A_{i\theta} = \left( p_i r + q_i \frac{1}{r} \right) \left( s_i + t_i z \right)
\]

\[
+ \sum_{n=1}^{\infty} \left[ a_{in} J_1(k_n r) + b_{in} Y_1(k_n r) \right]
\]

\[
\times \left[ c_{in} e^{k_n z} + d_{in} e^{-k_n z} \right]
\]

\[
+ \left[ e_{in} J_1(m_n r) + f_{in} K_1(m_n r) \right]
\]

\[
\times \left[ g_{in} \cos(m_n z) + h_{in} \sin(m_n z) \right]
\]

where \( J_1(kr) \) and \( Y_1(kr) \) are Bessel functions of the first and second kind, respectively; and \( J_1(mnr) \) and \( K_1(mnr) \) are modified Bessel functions of the first and second kind, respectively.

As the axial flux density is periodic, the exponential terms are

\[
c_{in} = 0 \quad d_{in} = 0.
\]

By taking the curl of magnetic vector potential \( \mathbf{A} \), the radial and axial flux densities are obtained as

\[
B_{ir} = \left( p_i r + q_i \frac{1}{r} \right) t_i
\]

\[
+ \sum_{n=1}^{\infty} m_n \left[ e_{in} J_1(m_n r) + f_{in} K_1(m_n r) \right] \sin(m_n z')
\]

\[
B_{iz} = 2(s_i + t_i) p_i
\]

\[
+ \sum_{n=1}^{\infty} m_n \left[ e_{in} I_0(m_n r) - f_{in} K_0(m_n r) \right] \cos(m_n z').
\]

2) **Magnetic Field in Current Region**: Magnetic field distribution in the current region is the solution to the Poisson’s equation (3). The solution to Poisson’s equation is the superposition of the homogeneous solution to Laplace’s equation and a particular solution to the Poisson’s equation. Substituting (4) into the right side of Poisson’s equation and using variable separation again yield

\[
Z(z) = \cos(m_n z')
\]

\[
(m_n r)^2 \frac{\partial^2 R}{\partial (m_n r)^2} + (m_n r) \frac{\partial R}{\partial (m_n r)} - \left[ 1 + (m_n r)^2 \right]
\]

\[
= P_n \frac{2(m_n r)^2}{\pi}
\]

where \( m_n \) and \( P_n \) are calculated with

\[
m_n = \frac{(2n - 1) \pi}{\tau_p}
\]

\[
P_n = -\pi \mu_0 J_n \frac{2 m_n^2}{m_n^2},
\]

A particular solution to Poisson’s equation employing Struve function [36] is given as

\[
A_{2\theta}^i = \sum_{n=1}^{\infty} L_1(m_n r) P_n \cos(m_n z').
\]
Therefore, the magnetic flux density in the current region is

\[
B_{2r} = \left(-p_2 r + q_2 \frac{1}{r}\right) t_2 \\
+ \sum_{n=1}^{\infty} m_n \left[e_{2n} I_1(m_n r) + f_{2n} K_1(m_n r)\right]
+ L_1(m_n r) P_n \sin (m_n z') \\
B_{2z} = 2(s_2 + t_2) p_2 \\
+ \sum_{n=1}^{\infty} m_n \left[e_{2n} I_0(m_n r) - f_{2n} K_0(m_n r)\right]
+ L_0(m_n r) P_n \cos (m_n z').
\]

(9)

3) Boundary Conditions: Boundary conditions are required to determine the unique solution of the magnetic field. Subjecting to Gauss’s law and Ampere’s law, magnetic field obeys certain rules along the boundary of two different materials. The component of magnetic flux density perpendicular to the boundary is always continuous, i.e., \(B_{1n} = B_{2n}\). The tangential component of magnetic field is discontinuous by the amount of surface current at the boundary, i.e., \(H_{1n} - H_{2n} = K\). In particular, in this paper, boundary conditions are

\[
B_{1z}|r=r_a = 0 \quad B_{3z}|r=r_a = 0 \\
B_{1r}|r=r_a = B_{2r}|r=r_a = H_{1z}|r=r_a = H_{2z}|r=r_a \\
B_{2r}|r=r_a = B_{3r}|r=r_a = H_{3z}|r=r_a.
\]

(10)

Through solving the boundary condition equations, the following constraints are obtained:

\[
p_1 = p_2 = p_3 = 0 \\
q_1 t_1 = q_2 t_2 = q_3 t_3 = -Q \]

\[
UX = Y
\]

(11)

where \(U\), \(X\), and \(Y\) are as defined in the equations shown at the bottom of the page. In coefficient matrix \(U\)

\[
r_1 = m_a r_1, \quad r_2 = m_a r_a, \quad r_3 = m_a r_b, \quad r_4 = m_a r_o.
\]

Therefore, the analytical expressions of flux density in Regions \(i (i = 1, 3)\) and \(2\) can be simplified to

\[
B_{1r} = \frac{Q}{r} + \sum_{n=1}^{\infty} m_n \left[e_{1n} I_1(m_n r) + f_{1n} K_1(m_n r)\right] \sin (m_n z')
\]

\[
B_{1z} = \sum_{n=1}^{\infty} m_n \left[e_{1n} I_0(m_n r) - f_{1n} K_0(m_n r)\right] \cos (m_n z')
\]

(12)

\[
B_{2r} = \frac{Q}{r} + \sum_{n=1}^{\infty} m_n \left[e_{2n} I_1(m_n r) + f_{2n} K_1(m_n r)\right]
+ L_1(m_n r) P_n \sin (m_n z')
\]

\[
B_{2z} = \sum_{n=1}^{\infty} m_n \left[e_{2n} I_0(m_n r) - f_{2n} K_0(m_n r)\right]
+ L_0(m_n r) P_n \cos (m_n z').
\]

(13)

To get the value of \(Q\) without complex computation, we utilize equivalent magnetic circuit (EMC), instead of analytical modeling based on harmonic expansion, to achieve a close solution. Since the waveform of the flux density is already determined in the analytical expression, \(Q\) is tolerable to estimate, and it will not decrease much the precision of the analytical model.

4) Coefficients Determination: The coil numbers, magnetic flow distribution, and EMC are shown in Fig. 5(a)-(c), respectively. For a machine with single phase winding consisting of \((2k + 1)\) coils, the MMF generated by the \(n\)th coil is

\[
F_n = (-1)^n N I, \quad n = -k, -(k - 1), \ldots, k - 1, k.
\]

(14)

Magnetic reluctance in the circuit is classified into three types, i.e.,

\[
R_n = \frac{g}{2\pi \mu_0 r_{tp}} \\
R_+ = \frac{g}{2\pi \mu_0 (l - z_r - k_{tp})} \\
R_- = \frac{g}{2\pi \mu_0 (l + z_r - k_{tp})}
\]

(15)
where $\bar{r}$ is the equivalent radii for gap reluctance, which is defined as

$$\bar{r} = \frac{r_o - r_i}{\ln(r_o/r_i)}.$$  

The magnetic circuit equations are given as

$$\phi_0 - \phi_{(k-1)} R_{(k-1)} = F_{-k}$$
$$\phi_n R_n - \phi_{n+1} R_{n+1} = F_n$$
$$\phi_k R_k - \phi_{+} R_{+} = F_k$$
$$\phi_- + \phi_+ + \sum_{n=-(k-1)}^{k} \phi_n = 0.$$  

(16)

By solving the preceding equations, the main magnetic flux between coil 1 and coil 0 ($\phi_1$) and that between coil 0 and coil $-1$ ($\phi_0$) is related with

$$\phi_1 \phi_0 = -l + (l)^{b} z_r.$$  

(17)

Meanwhile, $\phi_0$ and $\phi_1$ can be deduced from the analytical expression of flux density, i.e., (9), as

$$\phi_1 = \int_{z'=-3r_p/4}^{z'=3r_p/4} 2 \pi r B_{2r} dz'$$
$$\phi_0 = \int_{z'=-3r_p/4}^{z'=-3r_p/4} 2 \pi r B_{2r} dz'. $$  

where $r$ is an arbitrary number from $r_o$ to $r_b$. The range of $z'$ in (18) is obtained from the magnetic flow distribution in Fig. 5(b). By substituting (18) into (17), $Q$ is obtained as

$$Q = \frac{2(-1)^b \bar{r}}{l_{r_p}} \sum_{n=1}^{y_n} z_r$$

where

$$y_n = e_{2n} I_1 (n \bar{r}) + f_{2n} K_1 (n \bar{r}) + L_1 (n \bar{r}) P_n.$$  

Therefore, all coefficients in analytical models are determined.

IV. WINDING INDUCTANCE

Winding inductance influences system dynamics of electromagnetic machines significantly. Because of the employment of single phase winding, only self-inductance exists. Magnetic energy utilized to analyze the winding inductance is

$$W = \int \int \frac{B \cdot H}{2} dv = \frac{1}{2 \mu_0} \int \int B^2 dv.$$  

(19)

For Regions 1–3 (type 1), flux densities have been formulated, and the sum of energies in these areas is

$$W_a = W_1 + W_2 + W_3$$
$$= \frac{\pi}{\mu_0} \int_{z_b}^{z_a} (B_{1r}^2 + B_{1z}^2) r' dr' dz'$$

where the bound for $z'$ is

$$z_b = -(k r_p + \tau_p/2)$$
$$z_t = k r_p + \tau_p/2.$$  

(21)

For Regions 4 and 5 (type 2), the EMC method can provide a field model accurate enough for inductance computation. The energy in type 2 is

$$W_b = \frac{\pi}{\mu_0} \int_{z_a}^{z_b} \int_{r_i}^{r_o} B_{2r}^2 \frac{dr' dz'}{l_{r_p}}$$
$$= \frac{(R_0^2 - R_z^2)}{8 \pi \mu_0 r^2} \left[ \frac{\phi_z^2}{l - z_r - z_t} + \frac{\phi_z^2}{l + z_r + z_b} \right].$$  

(22)

The magnetic energy resulting from the inductance matrix of the five-coil winding is

$$W = \frac{1}{2} [L]^T [N_k I] [L]$$  

(23)

where

$$[L] = \begin{bmatrix}
L_{11} & M_{12} & M_{13} & M_{14} & M_{15} \\
M_{21} & L_{22} & M_{23} & M_{24} & M_{25} \\
M_{31} & M_{32} & L_{33} & M_{34} & M_{35} \\
M_{41} & M_{42} & M_{43} & L_{44} & M_{45} \\
M_{51} & M_{52} & M_{53} & M_{54} & L_{55}
\end{bmatrix}$$

$$[N_k I] = [N_k I_1\ N_k I_2\ N_k I_3\ N_k I_4\ N_k I_5]^T.$$  

Assume that the five coils in the winding are completely equivalent in the inductive characteristics, i.e.,

$$L_{ij} = L_{ji}, \quad i, j = 1, 2, \ldots, 5$$
$$M_{ij} = M_{ji}, \quad j \neq i.$$  

(24)

the self-inductance of a single coil is given. When referring to the principle that the winding inductance is proportional to the square of turns, the self-inductance of the single phase winding with five coils is

$$L_w = 5^2 L_{ii}.$$  

(25)

V. VALIDATION BY FEM

Although FEM is time consuming, it can achieve high-precision results, taking nonlinear characteristics and flux leakage into consideration. Therefore, FEM is utilized to validate the established analytical models, including magnetic field model and inductance model. The structure parameters of a five-coil PMTLM in FEM computation is given in Table I.
Fig. 6. Armature reaction field variation versus $z'$ validated by FEM. (a) Flux density at $r = (r_i + r_a)/2$. (b) Flux density at $r = (r_a + r_b)/2$. (c) Flux density at $r = (r_b + r_s)/2$.

A. Armature Reaction Field Validation

1) Flux Density Versus $z'$: Fig. 6(a)–(c) presents the flux density variation, including radial and axial components, versus axial distance $z'$ at $r = (r_1 + r_a)/2$, $r = (r_a + r_b)/2$, and $r = (r_b + r_s)/2$, respectively. Because the armature reaction field is influenced by the mover position $z_r$, the flux density variation for different $z_r$ is also shown in the figure. The solid curve is obtained at $z_r = 0$. It indicates that the winding locates at the center of the machine. The dotted curve is given at $z_r = 18$ mm, a pole pitch distance. It can be found that the mover position $z_r$ only affects the distribution of the radial flux component. It is mainly because magnetic reluctance change caused by mover translation is hardly related to the axial component, as indicated in Fig. 5. The analytical solutions fit well with the FEM results.

2) Flux Density Versus $r$: Fig. 7 presents the magnetic flux density variation versus radial distance at $z' = \tau_p/4$ for different mover position $z_r = 0$ and $z_r = \tau_p$. It also shows that the mover translation hardly affects the axial component of the magnetic flux density. The radial component decreases for large value versus radial distance $r$ because of the increased cross section for constant magnetic flux. The analytical solutions are consistent with the FEM results, which indicates that the analytical field model is of high precision comparable with numerical computation.

B. Inductance Validation

The relationship of self-inductance $L_{w}$ versus mover position $z_r$ is shown in Fig. 8. It is shown that the difference between the analytical solutions and numerical results is less than 3%, which implies that the inductance model can be employed for system dynamic analysis and control implementation. It also, in turn, verifies the high precision of the flux field model. The difference is mainly caused by the EMC method in the computation of magnetic energy.

C. Comparison With Finite-Length Model

Magnetic flux density components of armature reaction obtained by the developed mathematical model are compared with conventional analytical model for infinite machine length. The result is presented in Fig. 9. It shows that the developed
magnetic field model fits with the numerical computation well, which, in turn, indicates that the proposed method helps to improve mathematical modeling of magnetic field distribution.
ignorable in the winding. Therefore, two steps are carried out to measure the winding inductance. Specifically, Step 1 is to calculate the resistance of winding with a multimeter, and Step 2 is to measure the impedance by inputting alternating current with a frequency of 50 Hz. The schematic is shown in Fig. 13. The experimental devices are shown in Fig. 14. Comparison of analytical results, FEM computations, and experimental data is presented in Fig. 15. It is found that the three sets of data fit with each other quite well. The difference between the analytical and measurement results is mainly caused by the measurement error and the fabrication error of windings that may influence the parameters in the models. However, because the self-inductance of a coil is related with its neighboring field, the self-inductances of the five coils are not exactly the same. Meanwhile, the inductive coupling coefficient between two coils is less than 1, and thus, the mutual inductance is always less than the self-inductance. Therefore, (25), based on the assumption, leads to a relatively large difference between measurement data and analytical solutions.

Experiments are also conducted to test the linearity of the electromagnetic motor and, thus, to further validate the established mathematical models. Fig. 16 gives experimental results of maximum force output versus current input. The linear property can benefit the motion control implementation. The thrust per volume and the thrust per copper losses of different magnet topologies in given volume are investigated with FEM. The result shows that the dual Halbach array helps to increase force density of the system compared with single layer of magnet array. More study on the force output of the linear motor will be conducted at the next stage.

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Fig. 11. Armature field versus $z'$ for three-coil winding.

Fig. 12. Armature field versus $z'$ for five-coil winding.

Fig. 13. Schematic of inductance measurement.

Fig. 14. Inductance measurement on the research prototype.

Fig. 15. Inductance variation versus mover position $z_r$ validated by experiments.
VII. CONCLUSION

The analysis of armature reaction field is significant for high-precision motion control of electromagnetic machines. To improve the modeling precision, this paper has proposed a novel method to formulate the armature reaction field of a coreless moving-coil PMLM by taking finite motor field length into consideration. Winding inductance is subsequently analytically derived. The modeling approach has the merits of analytical technique based on harmonic expansion and EMC method. Numerical computations are utilized to verify the analytical models. The comparison shows that the mathematical models fit with numerical results closely. Furthermore, a research prototype of the linear machine is developed. Experiments are conducted to validate the mathematical models of armature reaction field and inductance. It indicates that the established models fit with the experimental results well. The study in this paper can help design optimization and motion control of linear machines. The proposed modeling method is effective and could be implemented into analysis of other electromagnetic machines.

REFERENCES


Liang Yan (M’07–SM’12) received the Bachelor’s degree from North China Institute of Technology, Shanxi, China, in 1995, the Master’s degree from Beijing Institute of Technology, Beijing, China, in 1998, and the Ph.D. degree from Nanyang Technological University (NTU), Singapore, in 2006. From 1998 to 2002, he was with Beijing Institute of Technology. From 2006 to 2009, he was with NTU. He is currently a Professor with Beihang University, Beijing. His research interests include robotics, actuators and sensors, and navigation systems.

Prof. Yan served as a Program and Publication Chairman for more than ten IEEE/ASME conferences.

Lei Zhang received the Bachelor’s degree from North China Electric Power University, Beijing, China, and the Master’s degree from Beihang University (BUAA), Beijing, in 2014. She is currently with the School of Automation Science and Electrical Engineering, Beihang University. Her research interests include electromagnetic actuators, sensors, and electrical circuit design.

Ms. Zhang was the recipient of the National Graduate Scholarship in 2013, the Graduate Innovation Fund in 2012, and the Excellent Master Thesis of Beihang University in 2014.

Zongxia Jiao received the B.S. and Ph.D. degrees from Zhejiang University, Zhejiang, China, in 1985 and 1991, respectively.

From 1991 to 1993, he was a Postdoctoral Fellow with Beihang University (BUAA), Beijing, China, where he has been a Professor since 1994 and is currently the Dean of the School of Automation Science and Electrical Engineering. His research interests include actuators, sensors, fluid power, and transmission.

Prof. Jiao was the recipient of the Changjiang Scholar and Leader Program in 2006 and the Distinguished Young Scholar of China.

Lei Zhang

Liang Yan

Chin-Yin Chen (M’95–SM’06–F’12) received the B.S. degree from National Sun Yat-sen University, Kaohsiung, Taiwan, in 2008. He is currently a Researcher with the Institute of Advanced Manufacturing Technology, Ningbo Institute of Material Technology and Engineering, Ningbo, China. His research interests include actuator design, mechatronics, integrated structure/control design, and robotics.

I-Ming Chen (M’95–SM’06–F’12) received the B.S. degree from National Taiwan University, Taipei, Taiwan, in 1986, and the M.S. and Ph.D. degrees from the California Institute of Technology, Pasadena, CA, USA, in 1989 and 1994, respectively. Since 1995, he has been with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, where he is also the Director of the Intelligent Systems Centre. His research interests include wearable sensors, human–robot interaction, reconfigurable automation, parallel kinematics machines, and smart material-based actuators.

Hongjie Hu received the Bachelor’s degree from Harbin University of Science and Technology, Harbin, China, in 1986, the Master’s degree from Harbin Institute of Technology, Harbin, in 1993, and the Ph.D. degree from Beihang University, Beijing, China, in 2002.

He was a Postdoctoral Fellow and a Lecturer with Beihang University, where he is currently an Associate Professor. His research interests include electrical machine design, mechanism design, control theory, and engineering.

I-Ming Chen

Chin-Yin Chen

I-Ming Chen

I-Ming Chen

I-Ming Chen

I-Ming Chen