IJCTA, 9(16), 2016, pp. 8115-8124

Efficient Wireless Power Transfer System for Generation of Magnetic Propulsion Torque for Microrobot

R. Narayanamoorthi*, A. Vimala Juliet* and A. Dominic Savio*

ABSTRACT

This paper aims to design an efficient wireless power transfer (WPT) system to power the microrobot. WPT system can generate propulsion force and torque as well as electrical energy to perform different tasks. The induced current and field from the WPT coils are utilized into the propulsion force and the Lorentz force for the rotational movement of the microrobot. The WPT model is designed on comsol multiphysics and the force and the torque are verified. Experimental setup also designed and tested with the simulation results on different parameters like mutual inductance, secondary voltage, torque and force

Keywords: Microrobots, Wireless power transfer, Magnetic Propulsion, Efficient WPT

1. INTRODUCTION

These days, various types of mobile microrobots have been used for various applications. In particular, in medical applications, the microrobots can provide minimally invasive surgery or drug infusion inside the body. Because of their small size, it can drift freely in the blood vessel to their specified destination. Therefore, the propulsion and the control mechanism of microrobots have become an active area of study in recent years [1], [2]. Based on recent studies, the propulsion of these robots is based on the insertion of permanent magnets with Helmholtz coil, which generate a magnetic field to control the microrobot. However, this type of propulsion system is limited in the sense that the dc magnetic field delivers propulsion without any electrical power to the robot [3]. Inevitably, the microrobot can only perform simple missions, such as drilling and moving, because they do not have any electrical power sources [4]. To supply electrical energy to the microrobots, a lot of research on battery powered microrobots have been performed recently [5]. Even though the battery size can be minimized, it also reduces battery capacity, which creates a problem of having a limited electrical energy source. If propulsion and power can be delivered to the microrobot simultaneously, the robot can contain active devices and can perform much more complex and important missions for medical purposes. Therefore, wireless power transfer (WPT) technology applications in the microrobots are being actively performed [6], [7]. Recent research adopted the Lorentz force as a source to obtain the propulsion while electrical energy is transferred, and this method uses a flexible ferrite sheet as a magnetic field shielding material to break the balance of Lorentz force for generating propulsion force [8][10]. In this paper, we propose a WPT system that can simultaneously deliver both the electric and dynamic energies to a robot, where the electric energy provides the power for active circuits, and the dynamic energy provides the control of propulsion force and torque of the microrobot. The WPT and the generation of propulsion force and torque are simulated using a 3-D electromagnetic field solver. The experiments with the fabricated coil structure verify the realization of the proposed generation of the forces.

* Faculty of Engineering and Technology, SRM University, Kattankulathur-603203, Chennai, India, *Email: narayanamoorthi.r@gmail.com*

2. WIRELESS POWER TRANSFER SYSTEM IN MICROROBOTS

Theconceptof a WPT system is shownin Fig. 1. Ina typical WPT system, when the time-varying current flows in a source coil, a magnetic field is generated, and then the generated magnetic field induces a current in the load coil, referred to as load current. Fig. 1(b) shows the equivalent circuit of WPT. The relationship between the source current and the load current is described as where I_L and I_S denote the phasor forms of the load coil current (I_L) and the source coil current (I_S), respectively. L_S, R_S, and C_S indicate the inductance, resistance, and capacitance of the source coil, respectively, and L_L, R_L, and C_L represent the inductance, resistance, and capacitance of the load coil, respectively. M is the mutual inductancebetween the source coil and the load coil, and ù is the angular frequency. The maximumpower is transferredat the resonance frequency, where the reactance of L_L and C_L cancel out each other. It should be noted that the phase difference between I_L and I_S is 90° in this condition [11]. The idea for generating propulsion force comes from an electromagnetconsistingofclosed-loopcoils. If the source coil and the loadcoil flow a time-varyingcurrent,theybehaveas an electromagnet, which can generate repulsive force and attractive force.When the incident magnetic field flows in the closed loop, each segment of the closed loop generates Lorentz force, which evidently can become a source of torque. Therefore, we focused on the magnetic force between electromagnets for propulsion, and the Lorentz force for rotation.

2.1. Microrobot Propulsion Using Electromagnets Force

In general, the magnetic force between two current-carrying coils can be derived from general expression aswhere I_1 and I_2 are the currents of two coils, M is their mutual inductance, and ZQ is the generalized coordinate [12]. If we adopt this theory to WPT, then the current I_1 and I_2 are simply replaced to I_S and I_L. Since the current I_S and I_L are time varying, the force between electromagnets is changed as well. The time-mean magnetic force in WPT is zero when the phase difference between I_S and I_L, represented as α, is 90° for the maximum power transmission. Eventually, the magnitude and the polarity of the magnetic force will change depending on the value of á. In addition, the α value can be controlled by changing the value of C_L in the load coil. By applying these characteristics, the magnetic force and the electrical power can simultaneously be delivered to the microrobot.

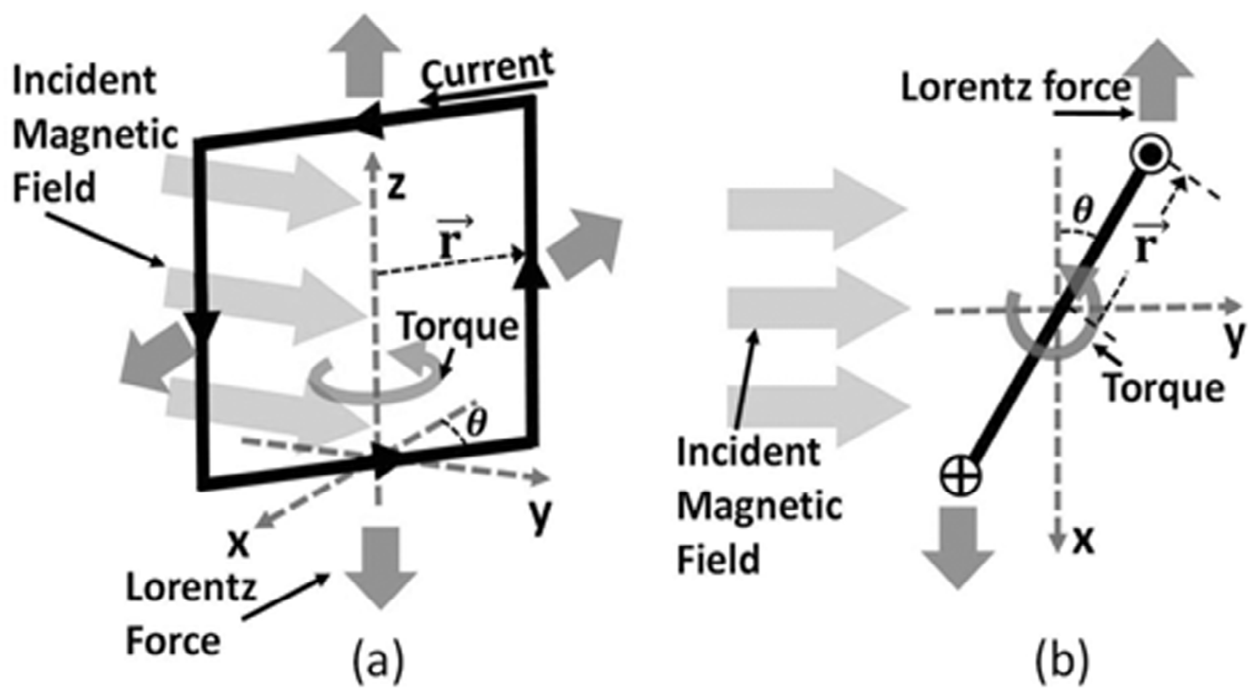
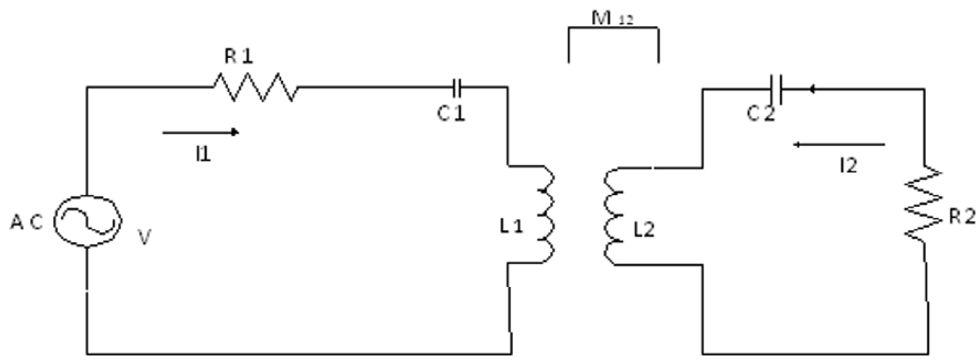


Figure 1: Lorentz force and torque when the incident magnetic field passes through the closed loop

Microrobot Rotation Through Lorentz Forces When the incident magnetic field is applied to the load coil, the Lorentz forces as well as the load current are generated in four segments of a closed loop. Fig. 2 shows the closed loop of the load coil which is not perpendicular to the incident magnetic field. Although the net force generated by the Lorentz force is canceled out by the symmetrical structure of the coil, torque generation still remains. A represent the torque vector, position vector from a chosen point to the point of the application of the force, magnitude of load current, applied force vector, and area of closed loop, respectively. B is the incident magnetic field generated from the source coil. However, as è varies, the load current changes as well, since mutual inductance is proportional to the cross-sectional area perpendicular to the incident magnetic vector area.

No torque is generated when è is 0° or 90°, while maximum torque is generated when the moment of angle is 45°. Using this phenomenon, the microrobot can generate torque, while the electrical energy is being transferred, allowing the microrobot to perform more complex missions in various areas.

Two coil wireless power system:



Fi

The above figure shows the equivalent cicuit for 2 coil wireless power power system.

Considering both circuits tuned at the same resonance angular frequency

$$\left(\omega_0^{-1} = \sqrt{L_1C_1} = \sqrt{L_2C_2}\right)$$

We can write the equation from the circuit,

$$v = R_1i_1 + j\omega_0M_{12}i_2 \quad (1)$$

$$0 = j\omega_0M_{12}i_1 + R_2i_2 \quad (2)$$

where, M_{12} is the mutual inductance, R_1 the total transmitting circuit resistance (including the internal resistances of the source and the involved capacitance (C_1) and inductance (L_1)), and R_2 is the total receiving circuit resistance (the sum of internal resistances of the involved capacitance (C_2) and inductance (L_2) with the load resistance)

$$R_2i_2 = -j\omega_0M_{12}i_1$$

$$i_1 = -\frac{R_2i_2}{j\omega_0M_{12}}$$

$$i_2 = -\frac{j\omega_0M_{12}i_1}{R_2}$$

Put the value of i_1 and i_2 from (2) in the equation (1),then we will get the equation for currents to get the equation of power

$$v = R_1 i_1 + \frac{\omega_0^2 M_{12}^2 i_1}{R_2}$$

$$= \frac{R_1 R_2 i_1 + \omega_0^2 M_{12}^2 i_1}{R_2}$$

$$= \frac{i_1\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)}{R_2}$$

$$i_1 = \frac{V R_2}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)}$$

$$v = \frac{-R_1 R_2 i_2}{j\omega_0 M_{12}} + j\omega_0 M_{12} i_2$$

$$= \frac{-R_1 R_2 i_2 - \omega_0^2 M_{12}^2 i_2}{j\omega_0 M_{12}}$$

$$= -\frac{i_2\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)}{j\omega_0 M_{12}}$$

$$i_2 = -\frac{V j\omega_0 M_{12}}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)} \tag{4}$$

Electric power is calculated multiplying the resistance by the square of the current amplitude so that using (1) (2) (3) and (4) it can be written

$$P_1 = i_1^2 R_1 \tag{5}$$

$$P_2 = i_2^2 R_2 \tag{6}$$

Put the value (3) and (4) in (5) and (6) then we will get

$$P_1 = \frac{v^2 R_2^2 R_1}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)^2} \tag{7}$$

$$P_2 = \frac{v^2 \omega_0^2 M_{12}^2 R_2}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)^2} \tag{8}$$

where, P_1 and P_2 are the electric power dissipated at R_1 and R_2, respectively.

Now we can calculate the efficiency using (7) and (8) in the equation (9)

$$\eta = \frac{P_2}{P_1 + P_2} \tag{9}$$

$$= \frac{\dfrac{v^2 R_2 R_1^2}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)^2}}{\dfrac{v^2 \omega_0^2 M_{12}^2 R_2}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)^2} + \dfrac{v^2 R_2 R_1^2}{\left(R_1 R_2 + \omega_0^2 M_{12}^2\right)^2}}$$

$$\eta = \frac{v^2 R_2 R_1^2}{v^2 \omega_0^2 M_{12}^2 R_2 + v^2 R_2 R_1^2} \tag{10}$$

The above equation (10) is the formula for efficiency of the 2 coil system

3. SIMULATION OF THE PROPULSION AND TORQUE

To illustrate the feasibility of propulsion and torque generation in load coil which is attached in microrobot, the simulations were conducted using a 3-D (Finite Element Method) FEM tool named ANSYS Maxwell as a field simulator and Agilent ADS as a circuit simulator. The simulation was performed for two cases: 1) the generation of propulsion force and 2) the torque. The simulation procedure consists of three stages. In the first stage, a 3-D field simulation to find the magnetic field distribution and induced voltage is performed. In the second stage, the induced current at the load coil is simulated using the circuit simulatorconsideringthe resonantWPT circuit. The load coil capacitance (C_L) is tuned to have maximum current at the load coil. At the final stage, the propulsion force and the torque are simulated using a 3-D field solver again, based on the induced current from the circuit simulation and incident magnetic field from the source coil. When

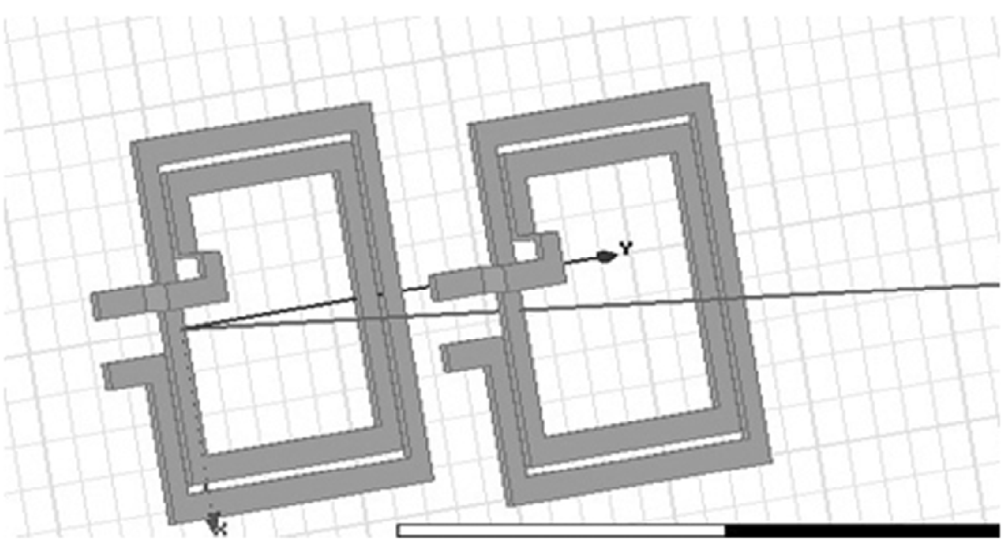
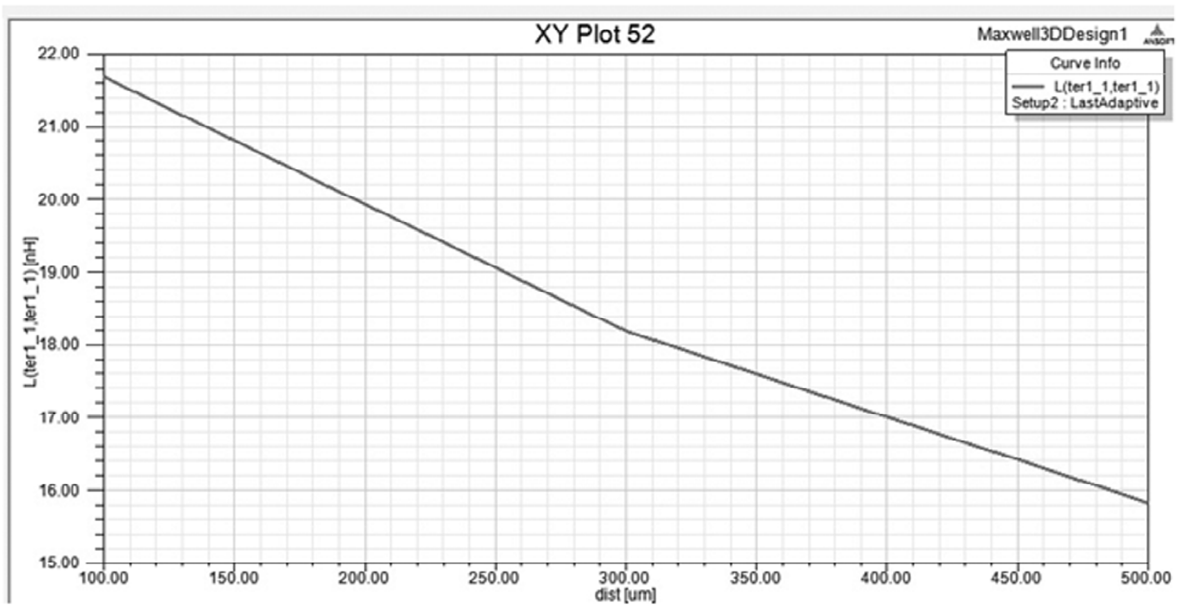


Figure 3: Two coil Simulation setup for each cases

L1



L2

Coupling Coefficient

Figure 4: The measured self and mutual inductance

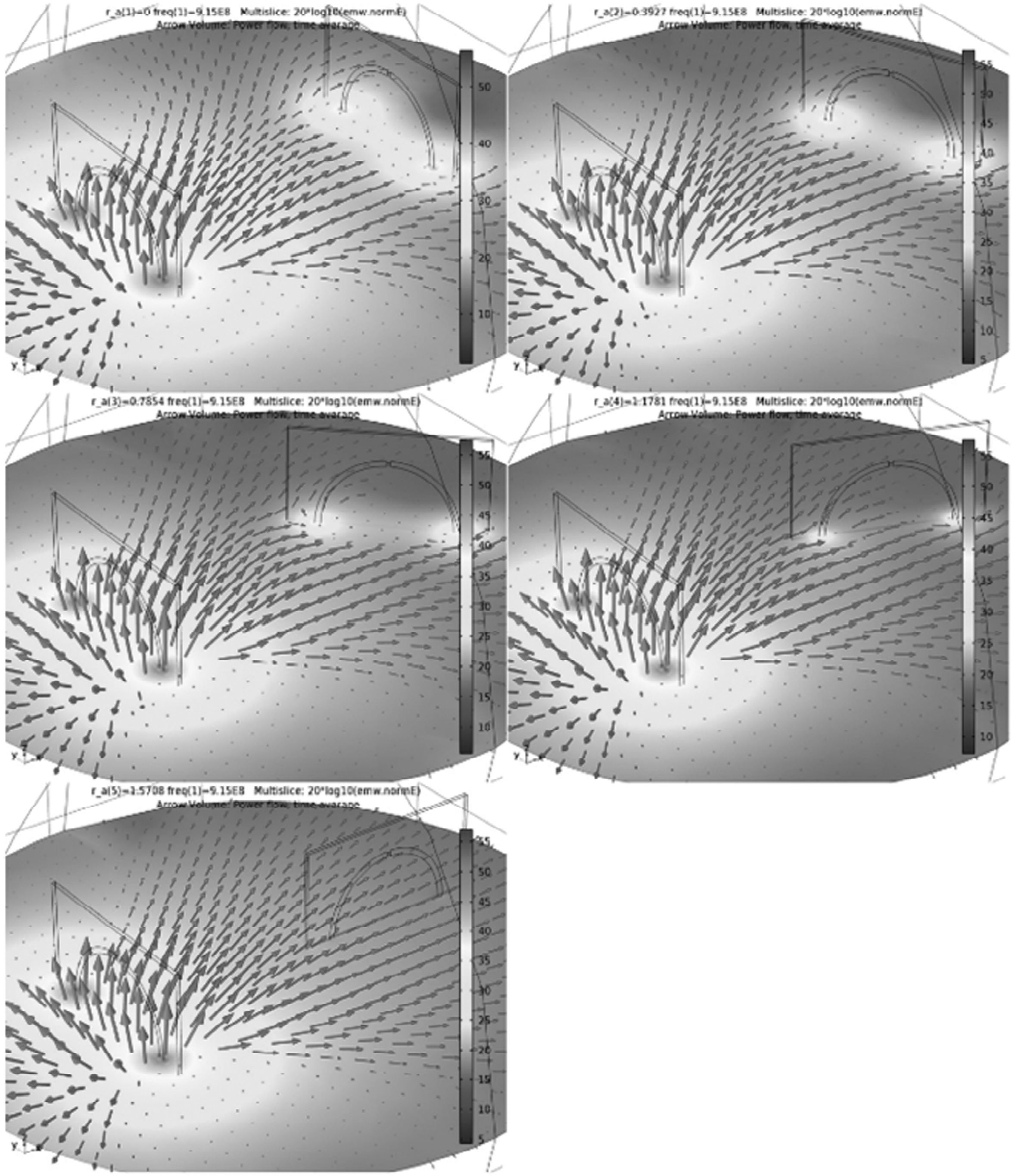


Figure 5: The E-Field norm and power flow

performing simulation for the propulsion force, it is assumed that the normal vector of the load coil is parallel to the incident magnetic field, as shown in Fig. 3(a). This is because the magnetic force between the source coil and the load coil is most effective on the direction that is parallel with the magnetic field direction. In this case, since the strength of the Lorentz force generated in each segment of the load coil is at perfect symmetrical configuration, no torque is generated. In contrast, when performing simulation for torque, the normal vector of the load coil is not parallel to the incident magnetic field, as shown in Fig. 3(b). Therefore, Lorentz force can be generated by an asymmetric magnetic field at each segment of the load coil. For simulation of torque generation, the angle (è) between the normal vector of the load coil and the incident magnetic field vector is changed by 5° in step. The simulation results will be compared with the experimental results in Section IV.

4. EXPERIMENTAL VERIFICATION.

Implementation of a Microrobots with WPT Coil to verify the simulation results of the propulsion force and torque generation, an up-scaled microrobot with wirelessly charging load coil was implemented for the experimental verification. A 100-turn circular coil carrying a 5 A current with the frequency of 20 kHz was designed as a source coil. In order to reduce the resistance, a Litz wire was used for the coil winding. The magnetic field generated by the source coil can reach a 25-turn square-shaped load coil which is located 10 cm away from the source coil. The dimensions of the fabricated coils are shown in Fig. 4, and the detailed electrical parameters of the coils are listed in Table I. In the experiment for the generation of propulsion, a capacitor was connected to the load coil in order to control the phase difference between the source current and the load current, as shown in Fig. 5. In the experiment for the generation of torque, the angle between the incident magnetic field and the normalvector of the load coil was changedfrom0° to 90° with 15° intervals. In case of torque generation, the capacitance was designed as 4.22ìF, which allows the phase difference between the source current and the load current to be 45°, resulting in the maximum torque.

The microrobot with load coil was mounted on a small Styrofoam ship floating on water, as shown in Fig. 4, to verify the generated propulsion force and the torque. For accurate measurement, the motions of the ship were recorded through video, and the velocity and angular velocity were precisely measured from the frame-by-frame analysis of the recorded video. After the velocity and angular velocity of the ship were measured, they were converted into the propulsion force and the torque using the following equations, respectively: Fprop denotes the propulsion force of the ship, which is identical to the total resistance force of the ship; RT denotes the ship moving in constant velocity; CD1 denotes the drag coefficient of the ship for the propulsion force experiment; ñ denotes the density of water; V denotes the velocity of the ship; and S1 denotes the wetted area of the ship. In (7), the relationship between the torque and the angular velocity in fluid conditions is indicated [13]. As different types of Styrofoam ships were designed in the experiments of propulsion generation and torque generation, the experimental parameters of the each experiment are listed in Table I [14].

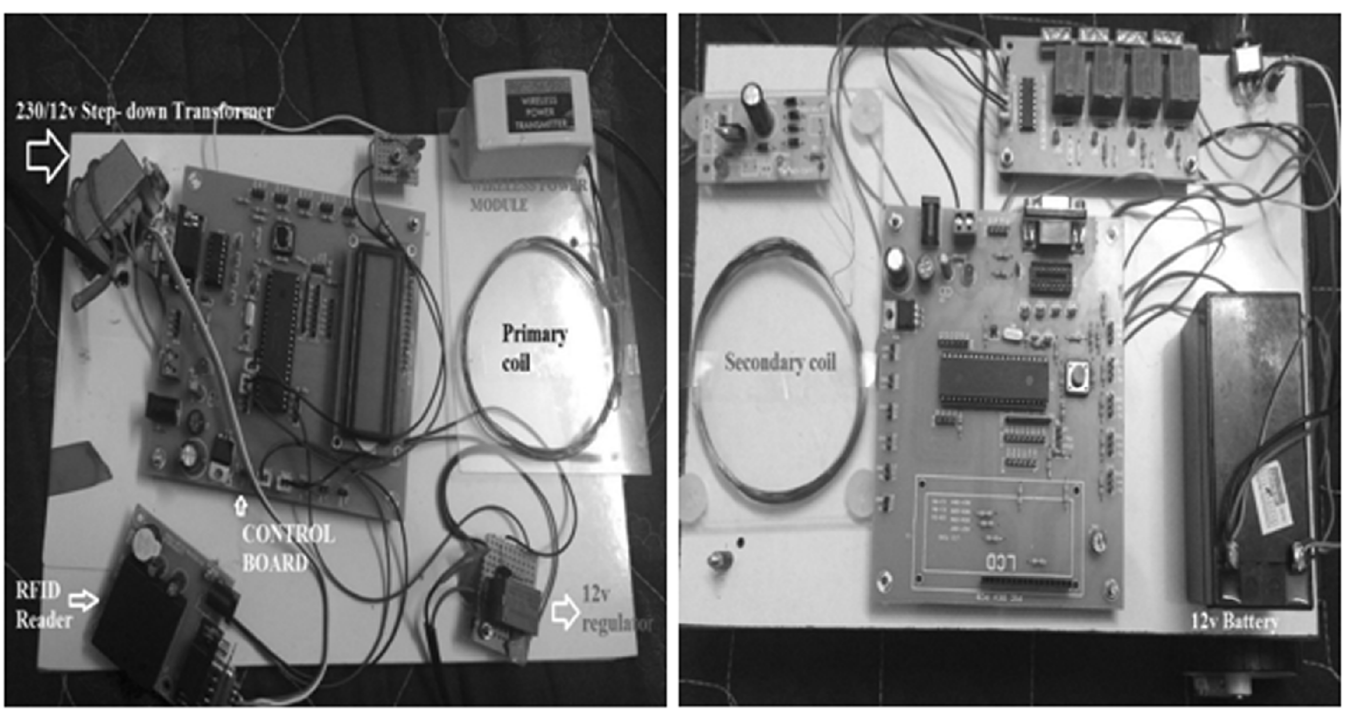


Figure 6: Robot Experiment Model

4.1. Results of Propulsion and Torque

Table 1 shows the comparison of simulated and measured propulsion forces. The magnitude and direction of the propulsion force is changed depending on the phase difference, á. For example, when á is <90°, the generated propulsion force is negative, result movement attracting to the source coil. The simulated and measured results correspond well with (3). The peak propulsion forces are observed when á is 45° and 135°, and the velocity of microrobot is 5.5 mm/s. In this condition, the received power at the load is 0.78 W, while the power consumption in primary circuit was 3.02 W. Fig. 7 shows the relation between the angle (è) of the incident magnetic field, the normal vector of the load coil, and the generated torque. The simulated and measured results indicate that the maximum torque occurs at 45°, which corresponds well with (5). When the torque is generated, the propulsion force is also generated; however, the propulsion force is much smaller than the Lorentz force which is the source of torque. Considering the torque of 185 ìNm at 45° in Fig. 7 is equivalent to 6167 ìN of Lorentz force, the propulsion force of 33 ìN is negligible.

Table 1
Experimental Measurements

Parameter	*Source cell*	*Load cell*
Self-inductance	2.35mH	22.97uH
Mutual-inductance		1.095uH
Resistance	0.2 ohm	1 ohm

5. CONCLUSION

This paper proposed a novel microrobot which can generate both the propulsion force and the torque by means ofWPT technology.The main idea is to utilize the magnetic field generated from the source coil to give the propulsion force and the Lorentz force to produce torque for the microrobot. Depending on the phase difference between the source current and the load current,the magnitudeand direction of propulsion force changes. In addition, depending on the angle between the incident magnetic field and the normal vector of the load coil, the magnitude of the generated torque also changes. The proposed microrobot that can generate both the propulsion force and the torque has successfully been validated by FEM simulations and verified through the experimental measurements.

REFERENCES

[1] K. B. Yesin, K. Vollmers, and B. J. Nelson, “Modeling and control of untethered biomicrorobots in a fluidic environment using electromagnetic fields,” Int. J. Robot. Res., vol. 25, nos. 5–6, pp. 527–536, May 2007.

[2] B. J. Nelson, I. K. Kaliakatsos, and J. J. Abbott, “Microrobots for minimally invasive medicine,” Annu. Rev. Biomed. Eng., vol. 12, pp. 55–85, Aug. 2010.

[3] A. W.Mahoney, N. D. Nelson, K. E.Peyer, B. J. Nelson, and J. J. Abbott, “Behavior of rotating magnetic microrobots above the step-out frequency with application to control of multi-microrobot systems,” Appl. Phys. Lett., vol. 104, no. 14, pp. 144101-1–144101-4, Apr. 2014.

[4] S. Palagi, B. Mazzolai, C. Innocenti, C. Sangregorio, and L. Beccai, “How does buoyancy of hydrogel microrobots affect their magnetic propulsion in liquids?” Appl. Phys. Lett., vol. 102, no. 12, pp. 124102-1–124102-5, Mar. 2013.

[5] H. Ishihara, F. Arai, and T. Fukuda, “Micro mechatronics and micro actuators,” IEEE/ASME Trans. Mechatronics, vol. 1, no. 1, pp. 68–79, Mar. 1996.

[6] W. H. Xin, G. Z. Yan, and W. X. Wang, “A stable wireless energy transmission system for gastrointestinal microsystems,” J. Med. Eng. Technol., vol. 34, no. 1, pp. 64–70, Jan. 2010.

[7] S. Rahimi and K. Takahata, “A wireless implantable drug delivery device with hydrogel microvalves controlled by field-frequency tuning,” in Proc. IEEE 24th Int. Conf. Micro Electro Mech. Syst. (MEMS), Jan. 2011, pp. 1019–1022.

[8] D. C. J. Krop, E. A. Lomonova, J. W. Jansen, and J. J. H. Paulides, “A study on the integration of contactless energy transfer in the end teeth of a PM synchronous linear motor,” J. Appl. Phys., vol. 105, no. 7, p. 07F115, Mar. 2009.

[9] D. Pivonka, A. S. Y. Poon, and T. H. Meng, “Locomotive micro-implant with active electromagnetic propulsion,” in Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC), Sep. 2009, pp. 6404–6407.

[10] D. Kim, M. Kim, J. Yoo, H.-H. Park, and S. Ahn, “Magnetic resonant wireless power transfer for propulsion of implantable micro-robot,” in Proc. 59th Annu. Conf. Magn. Magn. Mater., Nov. 2014, pp. 724–725.

[11] J. Kim et al., “Coil design and shielding methods for a magnetic resonant wireless power transfer system,” Proc. IEEE, vol. 101, no. 6, pp. 1332–1342, Jun. 2013.

[12] S. I. Babic and C. Akyel, “Magnetic force calculation between thin coaxial circular coils in air,” IEEE Trans. Magn., vol. 44, no. 4, pp. 445–452, Apr. 2008.

[13] V. Bertram, Practical Ship Hydrodynamics. Burlington, MA, USA: Butterworth-Heinemann, 2000, pp. 62–73. [14] F. M. White, Fluid Mechanics, 4th ed. New York, NY, USA: McGraw-Hill, 1998, pp. 458–460.