

Mid-range Wireless Power Transmission in Space

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Wireless power transmission using magnetic resonance is discussed. Theoretical transmission efficiency was derived as a function of impedance ratio r and RF frequency ω . Impedance matching is possible to attain maximum transmission efficiency for various coupling coefficient cases. Power feeding demonstration to an electric powered helicopter was conducted to develop an efficient, compact, and light-weight resonator as a receiver and to show the validity of the theoretical prediction. In this system, dielectric loss of the capacitor was found predominant and is limiting the quality factor Q of the resonator.

Nomenclature

C	= capacitance
fom	= figure-of-merit, $fom=kQ=\omega_0M/(R_S R_D)^{1/2}$
I	= complex electric current
k	= coupling coefficient, $k=M/(L_S L_D)^{1/2}$
L	= self inductance
M	= mutual inductance
Q	= quality factor of resonator, $Q=\omega_0 L/R$
R	= resistance of electric circuit
r	= impedance ratio, $r=Z_0/R$
V	= complex electric voltage
Z	= complex characteristic impedance, $Z=R+j(\omega L - 1/\omega C)$
η	= transmission efficiency
θ	= phase difference
ω	= angular velocity

Subscripts

S	= source, transmitter side
D	= device, receiver side
src	= power source
ld	= load

I. Introduction

Mid-range wireless power transmission technology is now in demand for power feeding to various applications such as electric cars, micro-robots, battery-less sensors etc. Since the year of 2007, the wireless power technology using a set of two resonating coils called “strongly coupled magnetic resonances” has been attracting attentions¹⁻³. A feature of this technology is high transmission efficiency in meter-order range. This technology is also applicable in space to power feeding to a spinning satellite, power transmission between mother and daughter satellites (Fig.1) and that among the constellation satellites. For example, given the actual conditions of study,

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daughter satellites can obtain feeding energy by 40% efficiency at the distance of 2.0[m] when the radius of resonator is 0.6[m].¹

It is important to know how to achieve optimum resonance conditions for a various gap and attitude between transmitter and receiver resonators in three dimensional space. In Section II, a formula for the transmission efficiency was developed based on the electric circuit theory. Here, two important non-dimensional parameters, a coil quality factor Q and induction coupling coefficient k , are introduced. Although the transmission efficiency has been known as a function of kQ for inductive power transmission, it is also valid for resonance power transmission.

In Section III, power feeding demonstration to an electric-powered helicopter has been reported. The aim of this demonstration is to develop an efficient, compact, and light-weight resonator as a receiver as well as to show the validity of the theory.

II. THEORY OF THE MID-RANGE POWER TRANSMISSION

A. Coupled Series LCR resonators

The model of power transmission system of the strongly-coupled magnetic resonance is the same as that of the inductively coupled series LCR resonators as shown in Fig.2 Kirchhoff's second law is expressed as,

$$\begin{bmatrix} V_{\text{src}} \\ 0 \end{bmatrix} = \begin{bmatrix} Z_S & j\omega M_{SD} \\ j\omega M_{SD} & Z_D + Z_0 \end{bmatrix} \begin{bmatrix} I_{\text{src}} \\ I_{\text{ld}} \end{bmatrix} \quad (1)$$

The currents flowing through source and load are derived as

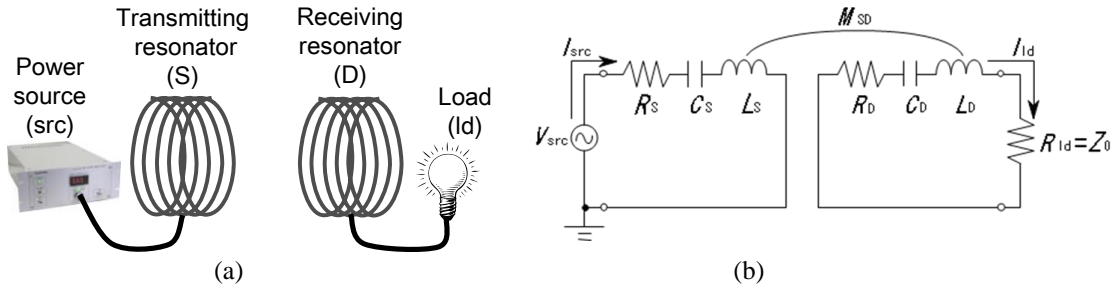


Fig. 2. Schematic of the system (a) and a circuit model (b).

$$\begin{bmatrix} I_{\text{src}} \\ I_{\text{ld}} \end{bmatrix} = \frac{V_{\text{src}}}{Z_S(Z_D + Z_0) + (\omega M_{SD})^2} \begin{bmatrix} Z_D + Z_0 \\ -j\omega M_{SD} \end{bmatrix} \quad (2)$$

B. Transmission Efficiency

Because the source frequency is often set to as high as 10 MHz, the concept of incident wave, reflected wave and transmitted wave should be introduced⁴. As Fig.3 shows, the coupled resonators inserted between the source and the load can be considered as a two-port network unit. Voltage amplitude of the incident wave from the source is $V_i = (V_{\text{src}} + Z_0 I_{\text{src}})/2$ and that of reflected and transmitted waves are $V_r = (V_{\text{src}} - Z_0 I_{\text{src}})/2$ and $V_t = Z_0 I_{\text{ld}}$, respectively. Then the transmission efficiency is defined as the ratio of transmitted wave power and incident wave power as

$$\eta = \left| \frac{V_t}{V_i} \right|^2 = \left| \frac{2i\omega M_{SD} Z_0}{(Z_S + Z_0)(Z_D + Z_0) + (\omega M_{SD})^2} \right|^2 \quad (3)$$

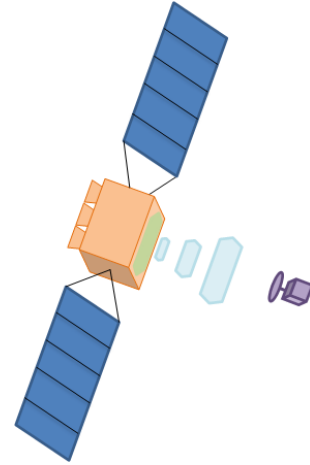


Fig. 1. An image of power feeding between mother and daughter satellites.

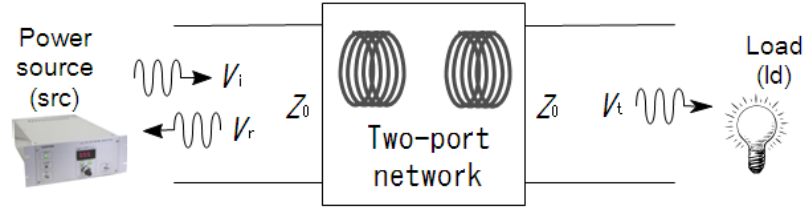


Fig. 3. Image of coupled resonators as a two-port network

In some cases such as low frequency operations, power source reuses reflected power and transmission efficiency⁵.

When the resonant frequencies are assumed to be equal to each other, $(L_S C_S)^{-1/2} = (L_D C_D)^{-1/2} = \omega_0$ and an frequency band is to be narrow enough $|\omega - \omega_0| \ll \omega_0$ for simplicity. η is expressed as follows using the approximations $\omega/\omega_0 - \omega_0/\omega \approx 2(\omega - \omega_0)/\omega_0$ and $\omega \approx \omega_0$.

$$\eta \approx \frac{4k^2 \frac{r_S}{Q_S} \frac{r_D}{Q_D}}{\left[k^2 - 4 \left(\frac{\omega - \omega_0}{\omega_0} \right)^2 + \frac{1+r_S}{Q_S} \frac{1+r_D}{Q_D} \right]^2 + 4 \left(\frac{\omega - \omega_0}{\omega_0} \right)^2 \left(\frac{1+r_S}{Q_S} + \frac{1+r_D}{Q_D} \right)^2} \quad (4)$$

In the ω - r_S - r_D domain, η has its maximum value at

$$\omega = \omega_0, \quad r_S = r_D = \sqrt{1 + k^2 Q_S Q_D} = \sqrt{1 + fom^2} \quad (5)$$

The maximum efficiency is expressed as

$$\eta_{\max} = \frac{fom^2}{\left(1 + \sqrt{1 + fom^2} \right)^2} \quad (6)$$

The physical meaning of Eq.(5) is the condition of the impedance matching. In the case $r_S = r_D$, an efficiency peak exists in the ω - r coordinate as shown in Fig.4⁵.

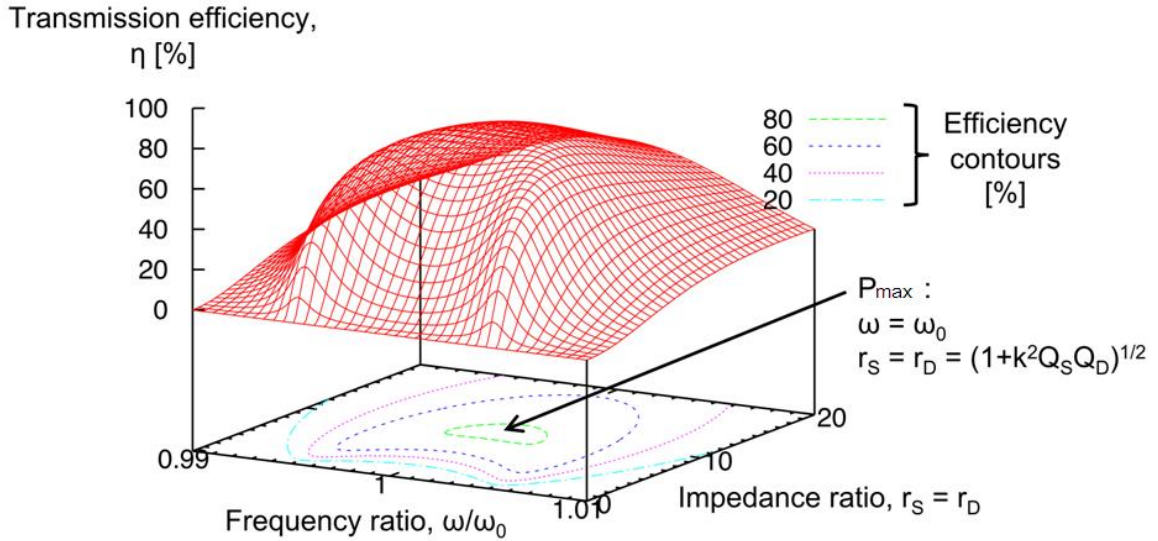


Fig. 4. Characteristics of transmission efficiency in the ω - r domain with $k = 0.01$ and $Q_S = Q_D = 1000$

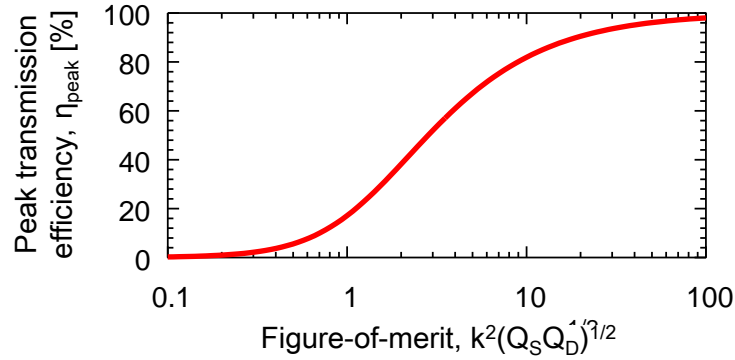


Fig. 5. Peak transmission efficiency plotted along figure-of-merit

Equation (6) depends only on $fom(=kQ)$ as shown in Fig.5. When fom is of the order of 10^0 or higher, power transmission would be possible at over 20 % of efficiency. When transmission distance is equal to or greater than the size of resonators, k becomes very low value of 10^{-2} or lower order. However, even with very low k , efficient wireless power transmission is possible using resonators having high Q of the order of 100 to 1000.

The parametric dependence of transmission efficiency is shown in Fig.6. Especially in the case of large k , the peak of efficiency is split.

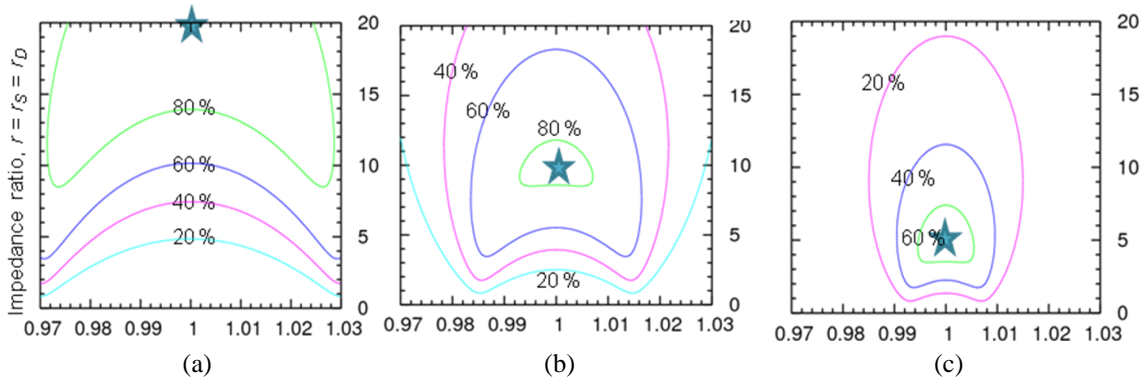


Fig. 6. Transmission efficiency in the ω - r domain. (a) $z/l=0.7$ ($k=0.06$), (b) $z/l=1$ ($k=0.03$), (c) $z/l=1.4$ ($k=0.015$).

III. Power feeding demonstration to an electric helicopter

A. Objectives of the Demonstration

The power feeding demonstration was conducted from the transmitter resonator on the ground to a helicopter in air. As stated before, the peak of the efficiency shifts as k (=altitude) changes. This indicates the importance of impedance matching for power feeding to mobile objects in 3-D space. The objective of this demonstration is to validate the theoretical relation between transmission distance and efficiency. Another objective is to develop an efficient, compact, and light-weight resonator as a receiver.

An electric-powered toy helicopter (Fig.7) is used. A receiver resonator, pickup coil and rectification circuit are mounted on the helicopter. The resonator is made of a copper pipe, whose outer diameter is 4 mm. A pickup coil is made of a copper foil to reduce the weight and drag. This pick up coil is connected to motor through a bridge circuit of four Shottky diodes (1SS99). The transmitter wave frequency is 40.68MHz.

B. Resonator Design

The resonators consist of a rectangular loop and a mica condenser. Side length of the loop and capacitance of the mica condenser were selected for the resonators to have a character frequency exactly equal to 40.68MHz. Table I

shows estimated resistance and Q . The dielectric loss in mica capacitors is the predominant energy loss mechanism an limiting Q for both resonators.

Furthermore, Ohm loss in the receiver resonator is also large because of its cross-sectional shape. Although the receiver resonator is composed by a copper pipe to reduce its weight, cross-sectional area is also reduced and ohm loss is increased.

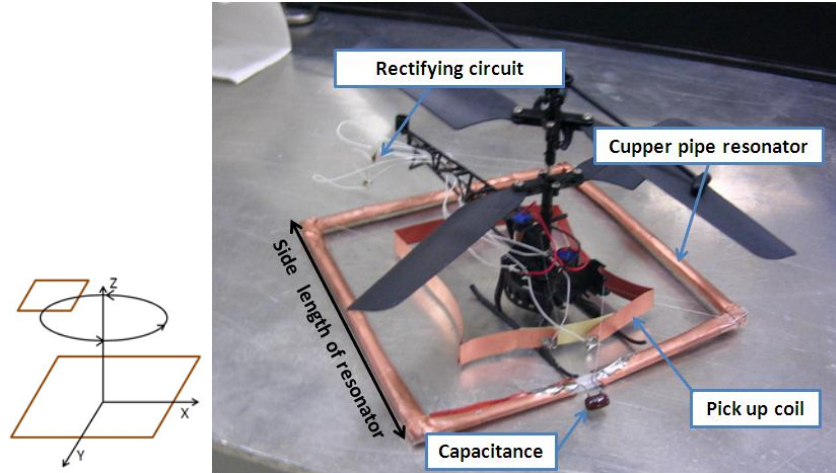


Fig. 7. A helicopter with a receiver resonator and a pickup coil.

Table 1. Resistance and Q of the resonators

	Transmitter resonator	Receiver resonator
Side length[mm]	353	113
Radiation R (theoretical)[Ω]	3.14E-02	2.45E-04
Ohm R (theoretical) [Ω]	0.252	0.58
Dielectric R in (catalog) [Ω]	0.706	0.337
Q (estimated)	377	200
Q (measured)	51	238

C. Variation of Transmission Efficiency in the xy -plane

Figure 8 shows the theoretical transmission efficiency obtained by Eq. (4) when the helicopter moves in the xy -plane at $z=0.15$ m. The origin of the coordinate is set at the center of transmitter resonator as illustrated in Fig.7.

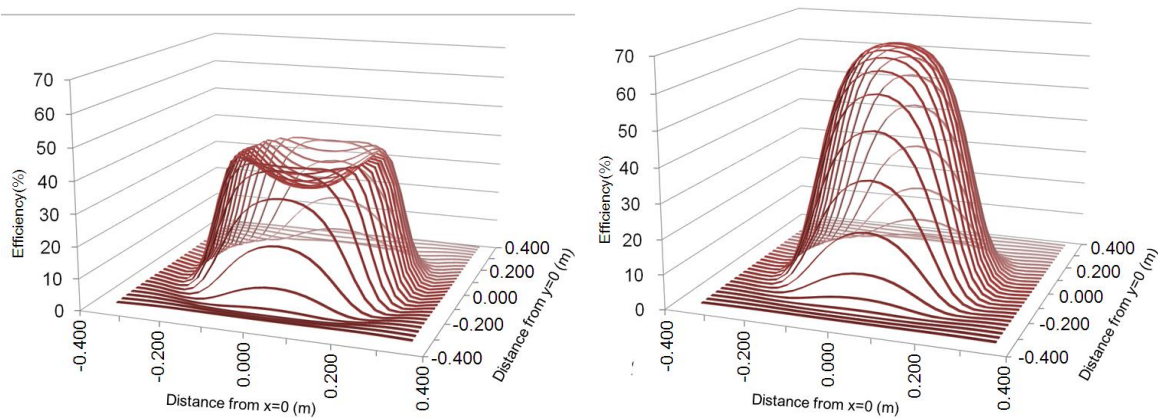


Fig. 8. Transmission efficiency in the xy -plane. Left: no impedance matching, right: with impedance matching at $(x, y)=(0, 0)$.

As stated before, the efficiency has split when no impedance matching was conducted. On the other hand, it has a peak at $(x, y)=(0, 0)$ when impedance matching ($r = (1 + k^2 Q_S Q_D)^{1/2}$) is done there.

D. Transmission efficiency along z-axis

The transmission efficiency changes with the altitude z as well. Figure 9 shows the relationship between the efficiency and z . The ideal line is the efficiency curve when optimal impedance ratio is kept everywhere. On the other hand, the red line shows the efficiency with the constant impedance ratio optimized at $z=0.1\text{m}$. The behavior of a helicopter rotor is similar to it in demonstration.

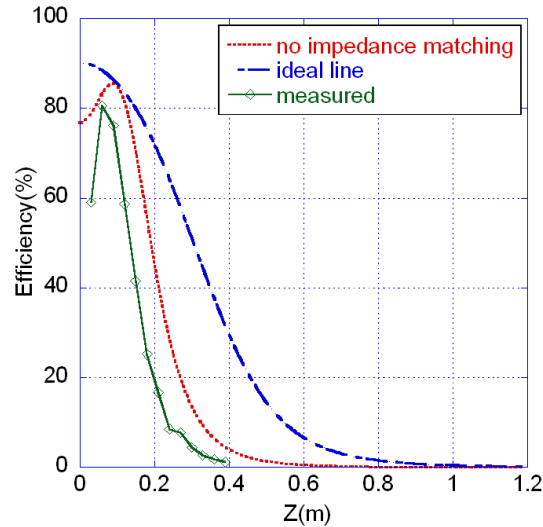


Figure 9. Transmission efficiency along the z-axis.

IV. Summary

- Theoretical efficiency of magnetic resonance power transmission is developed as a function of the impedance ratio r and RF frequency ω .
- Power feeding demonstration to a helicopter was conducted. Q is estimated by considering Ohm loss, radiation loss and dielectric loss in capacitor. As a result, the dielectric loss of the capacitor is found predominant and is limiting Q of the resonator.
- The relationship between the helicopter's position and transmission efficiency is computed for the cases with and without impedance matching and compared with the experiment.

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