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Position detection by Voltage Transmission between Two Printed Spiral Inductors

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Abstract— In this paper, we present a new position detection system with two printed spiral inductors(PS-Inductors). When the voltage transmission efficiency between first PS-Inductor and second PS-Inductor, which are not same PS-Inductor, is measured, value of the voltage transmission efficiency are observed with changing position. Position can be detected by using the characteristic values. We make clear to be able to construct the position detection system.

1. introduction

Recently, spiral inductor is used for chip inductor, on-chip inductor and so on. Therefore, a spiral antenna is used for RFID etc.. The spiral inductors and spiral antennas are developed rapidly. Especially, spiral antennas are used to RFID etc[1]-[3]. However, mutual inductance between two or more spiral inductors is not often used.

In this study, voltage transmission efficiencies between two printed spiral inductors (PS-Inductors) are investigated. If an alternate current of an arbitrary frequency is given to the primary PS-Inductor, an alternate current which has the same cycle of primary PS-Inductor is generated at the secondary PS-Inductor by the electromagnetic induction[4],[5]. Transmission efficiency is obtained from voltages of primary PS-Inductor and secondary PS-Inductor.

Firstly, voltage transmission efficiency between two same PS-Inductors is investigated as changing frequency. Next, by shape, size and the location of the secondary PS-Inductor is changed, transmission efficiencies are investigated. Finally, the new position detection system is constructed based on the above-mentioned measurement result. When secondary inductor at an arbitrary coordinate is existed, the voltage transmission efficiency($v1_{ik}$) is measured. The secondary inductor is rotated by an arbitrary angle. and the voltage transmission efficiency($v2_{ij}$) is measured. If a combination of $v1_{ik}$ and $v2_{ik}$ differs from combinations of $v1_{lm}$ and $v2_{lm}$ of all coordinates, position of secondary inductor can be determined by using $v1$ and $v2$, It is made clear that an angle, which the combination of $v1_{ik}$ and $v2_{ik}$ is unique value, exists. We make clear to be able to construct the position detection system.

2. Measurement of Inductance

The inductance of the PS-Inductor is given from following circuit (see Fig.1). This circuit shows the Colpitts oscillator. In setting up the circuit equation in this circuit, and assuming imaginary part =0, the following equations (1) are given.

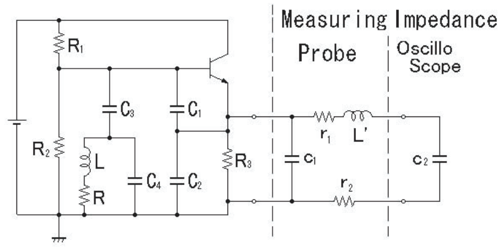


Figure 1: Circuit of inductance measurement

$$L = \frac{1 + \sqrt{1 - 4\eta^2 R^2}}{2\omega\eta} \tag{1}$$

where

$$\eta = (\omega C_4 + \frac{-\zeta}{\epsilon + \zeta})$$

$$\alpha = 1 - \omega^2(r_1 + r_2)R_3 c_2(c_1 + C_2) - \omega^2 c_2 L'$$

$$\beta = R_3(c_1 + c_2 + C_2) + c_2(r_1 + r_2) - \omega^2 L' R_3 c_2(c_1 + C_2)$$

$$\gamma = R_3 - \omega^2 c_2 R_3 L'$$

$$\delta = (r_1 + r_2)c_2 R_3$$

$$\epsilon = \frac{\alpha R_3 + \omega^2\beta\gamma}{\alpha^2 + \omega^2\beta^2}$$

$$\zeta = -\frac{1}{\omega}(\frac{1}{C_1} + \frac{1}{C_3}) + \frac{\omega(\alpha\gamma - \beta R_3)}{\alpha^2 + \omega^2\beta^2}.$$

3. Experiment

3.1. Transmission Efficiency of Same Inductors

Two PS-Inductors which have same characteristics are overlapped at a distance of 1.6[mm]. Voltage transmission efficiency between the primary and the secondary PS-Inductors is observed by using a circuit of Fig.2. The parameter is each $L1 = L2 = 11.0[\mu H], and C2 = 109[nF]$. The voltage transmission efficiency is obtained as follows.

$$Voltage\ Transmission\ Efficiency = \frac{V_2}{V_1}. \quad (2)$$

An observed phenomenon is shown in Fig.3. Vertical axis means voltage transmission efficiency, and horizontal axis means frequency. Maximum voltage transmission efficiency is observed when frequency is around 11.8[MHz]. Although two PS-Inductors are same parameters, maximum output voltage can be generated seven times of input voltage.

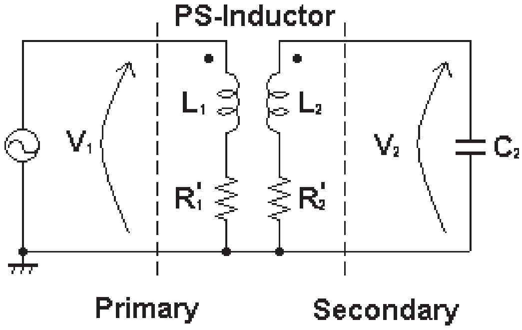


Figure 2: Circuit of measurement (same inductors).

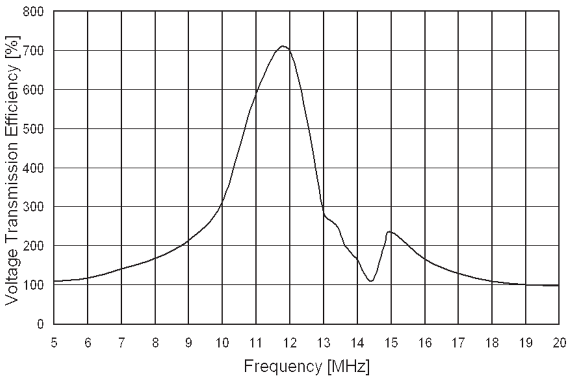


Figure 3: Voltage transmission efficiency between two same PS-Inductors.

3.2. Resonance Frequency

We prepare the PS-Inductors of the following specifications.

1. Primary inductor (see Fig.4)

   Maximum diameter(D_{max}) = 92.0[mm]
   Minimum diameter(D_{min}) = 4.0[mm]
   Number of half turns = 89[turns]
   Width of conductor = 0.2[mm]
   Distance between conductors = 0.8[mm]

2. Secondary inductor (see Fig.5)

As the secondary inductors, some half-circles which diameters respectively differ are prepared. The diameters (D) of half-circles are shown in Table 1.

C_2 is coupled to the secondary inductor (see Fig.2). The capacity of C_2 is set 106[nF] which is much larger than capacitance of a probe because of disregarding the influence

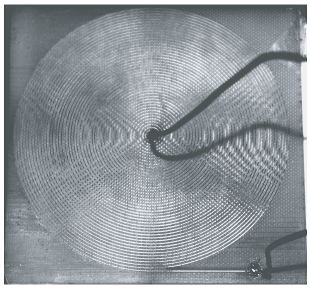


Figure 4: Primary inductor.

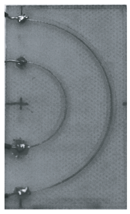


Figure 5: Sample of secondary inductor.

Table 1: Diameters of half circle.

Diameter (D) [mm]	Proportion to D_{max} [%]
23.0	25
46.0	50
69.0	75
92.0	100

of the capacitance of the probe. Centers of the primary inductor and secondary inductor are set to same location and proportion of secondary voltage to primary voltage is investigated changing frequency of input signal. Fig.6 shows the results. Theoretical resonance frequency is given by this equation.

$$f = \frac{1}{2\pi\sqrt{LC}}. \quad (3)$$

Table2 shows the theoretical value and the experimental result of resonance frequency.

We can observe that experimental results resemble to values of theory. The following measurements are used resonance frequencies of experimental result of Table 2.

3.3. Transmission Efficiency

3.3.1. Method of measurement

The transmission efficiency between primary and secondary is measured changing position of secondary half

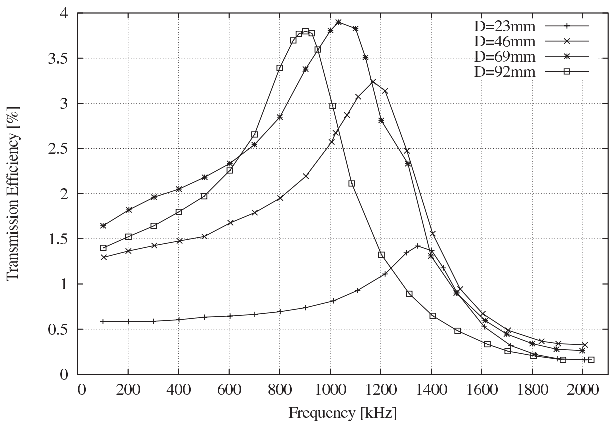


Figure 6: Frequency characteristic

Table 2: Resonance frequency of each inductor

Diameter	Measurements	Theoretically value
23.0	1.4	1.4
46.0	1.2	1.1
69.0	1.1	0.99
92.0	0.90	0.88
[mm]	[MHz]	[MHz]

circle inductor. The methods of changing the position is as follows:

1. The center of primary inductor and the center of secondary inductor are matched, and the center of primary is set as original point, and, x-axis and y-axis are provided.
2. The secondary inductor is moved at intervals of 5.0[mm] along x-axis and y-axis respectively.

3.3.2. Measurement result

The measurement results of Sec.3.3.1 are shown in Figs.8-11. The (a) of each Figs.8-11 expresses result of mapping to xz-plane.

When y=0, voltage proportions of each secondary inductor to primary inductor are shown in Fig.7. We can observe that voltage proportion depends on diameter of the secondary inductor.

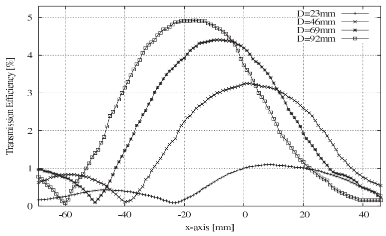
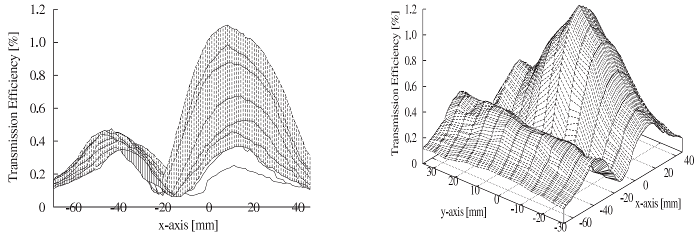


Figure 7: Voltage proportion of secondary to primary (y=0).

Six phenomena are observed as follows:

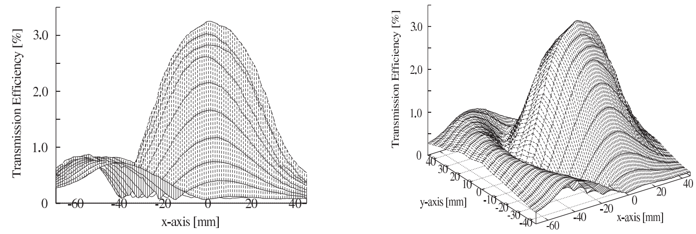
1. Maximum proportion of voltage exists on y-axis without influence of diameter of secondary PS-Inductor.
2. The second heights of local maximum are almost same.
3. A coordinate of maximum voltage proportion is changed to depend on diameter of secondary PS-Inductor.
4. A line where the voltage proportion is around zero existed.
5. Value of voltage proportion depend on the diameter of secondary PS-Inductor very much.
6. When D=23[mm] and y=-25[mm], line of minimum value is observed. We can not observe minimum value as other diameter of secondary PS-Inductors.



(a) Voltage proportion of secondary to primary (mapping to xz-plane).

(b) Voltage proportion of secondary to primary.

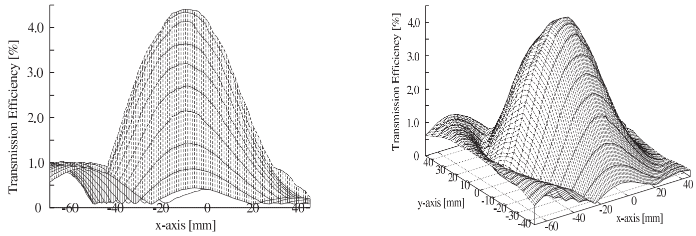
Figure 8: D=23.0(25%) [mm].



(a) Voltage proportion of secondary to primary (mapping to xz-plane).

(b) Voltage proportion of secondary to primary.

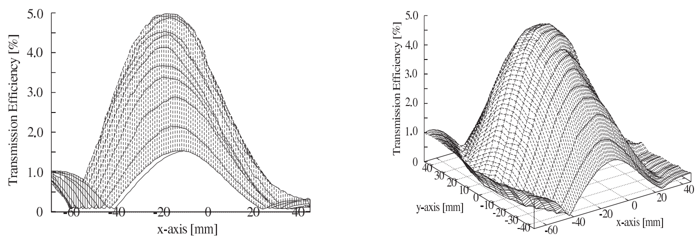
Figure 9: D=46.0 (50%) [mm].



(a) Voltage proportion of secondary to primary (mapping to xz-plane).

(b) Voltage proportion of secondary to primary.

Figure 10: D=69.0 (75%) [mm].



(a) Voltage proportion of secondary to primary (mapping to xz-plane).

(b) Voltage proportion of secondary to primary.

Figure 11: D=92.0 (100%) [mm].

3.4. Position detection

A system of position detection is constructed by using the results of the Sec.3.3.2. A voltage transmission efficiency of arbitrary coordinates (x, y) is expressed $v_1(x, y)$ A voltage transmission efficiency at (x, y) is expressed $v_2(x, y)$ when the secondary inductor is rotated an arbitrary angle. If a combination of $v_1(i, k)$ and $v_2(i, k)$ is unique for combinations at all other positions, the system of position detection can be constructed. We consider $v_1 v_2$-plane which is mapped from xy-plane. When $(v_1(0, 0), v_2(0, 0))$ is the reference point, the vectors are expressed as follows:

$$(v1_{ik}, v2_{ik}) = (v_1(i, k) - v_1(0, 0), v_2(i, k) - v_2(0, 0)) \qquad (4)$$

where

$$-\frac{D_{max}}{2} \leq i \leq \frac{D_{max}}{2}, \quad -\frac{D_{max}}{2} \leq k \leq \frac{D_{max}}{2}. \qquad (5)$$

When Eq.6 is satisfied, a combination of $v1_{ik}$ and $v2_{ik}$ is unique.

$$v1_{ik} \neq v1_{lm} \quad \text{or} \quad v2_{ik} \neq v2_{lm} \quad (i \neq l \ \text{or} \ k \neq m)\,. \qquad (6)$$

We investigate the arbitrary angle which satisfies these requirements. These requirements are satisfied when the secondary inductor is rotated 180 degrees and the diameter of secondary inductor equals 46[mm](see Fig.12).

x [mm]	y [mm]	v1 [%]	v2 [%]	x [mm]	y [mm]	v1 [%]	v2 [%]	x [mm]	y [mm]	v1 [%]	v2 [%]	x [mm]	y [mm]	v1 [%]	v2 [%]
-45	-45	0.6925	0.103	5	-20	2.11	0.628	0	10	2.735	0.1655	-5	40	0.1315	0.403
-40	-45	0.728	0.1095	10	-20	1.97	0.36	5	10	2.705	0.478	0	40	0.203	0.3625
-35	-45	0.6905	0.1115	15	-20	1.705	0.5	10	10	2.58	0.375	5	40	0.2375	0.2875
-30	-45	0.625	0.1155	20	-20	1.455	0.69	15	10	2.36	0.515	10	40	0.2415	0.225
-25	-45	0.519	0.103	25	-20	1.125	0.97	20	10	2.03	0.695	15	40	0.222	0.072
-20	-45	0.4185	0.1065	30	-20	0.83	1.33	25	10	1.595	0.99	20	40	0.175	0.219
-15	-45	0.303	0.097	35	-20	0.61	1.69	30	10	1.17	1.335	25	40	0.1405	0.378
-10	-45	0.2	0.0875	40	-20	0.455	2.045	35	10	0.845	1.725	30	40	0.1	0.522
-5	-45	0.1065	0.103	45	-20	0.33	2.345	40	10	0.595	2.08	35	40	0.0845	0.64
0	-45	0.0655	0.1565	-45	-15	0.515	2.47	45	10	0.42	2.315	40	40	0.0815	0.7125
5	-45	0.094	0.228	-40	-15	0.295	2.5	-45	15	0.64	2.515	45	40	0.0905	0.7375
10	-45	0.122	0.3125	-35	-15	0.28	2.39	-40	15	0.375	2.615	-45	45	0.7065	0.0875
15	-45	0.1175	0.403	-30	-15	0.655	2.22	-35	15	0.22	2.565	-40	45	0.7405	0.0815
20	-45	0.103	0.5125	-25	-15	1.08	1.905	-30	15	0.61	2.375	-35	45	0.7375	0.0845
25	-45	0.094	0.6125	-20	-15	1.595	1.485	-25	15	1.03	1.985	-30	45	0.7	0.0845
30	-45	0.0845	0.7	-15	-15	1.985	1.03	-20	15	1.485	1.595	-25	45	0.6125	0.094
35	-45	0.0845	0.7375	-10	-15	2.375	0.61	-15	15	1.905	1.08	-20	45	0.5125	0.103
40	-45	0.0815	0.7405	-5	-15	2.565	0.22	-10	15	2.22	0.655	-15	45	0.403	0.1175
45	-45	0.0875	0.7065	0	-15	2.615	0.375	-5	15	2.39	0.28	-10	45	0.3125	0.122
-45	-40	0.7375	0.0905	5	-15	2.515	0.64	0	15	2.5	0.295	-5	45	0.228	0.094
-40	-40	0.7125	0.0815	10	-15	2.315	0.42	5	15	2.47	0.515	0	45	0.1565	0.0655
-35	-40	0.64	0.0845	15	-15	2.08	0.595	10	15	2.345	0.33	5	45	0.103	0.1065
-30	-40	0.522	0.1	20	-15	1.725	0.845	15	15	2.045	0.455	10	45	0.0875	0.2
-25	-40	0.378	0.1405	25	-15	1.335	1.17	20	15	1.69	0.61	15	45	0.097	0.303
-20	-40	0.219	0.175	30	-15	0.99	1.595	25	15	1.33	0.83	20	45	0.1065	0.4185
-15	-40	0.072	0.222	35	-15	0.695	2.03	30	15	0.97	1.125	25	45	0.103	0.519
-10	-40	0.225	0.2415	40	-15	0.515	2.36	35	15	0.69	1.455	30	45	0.1155	0.625
-5	-40	0.2875	0.2375	45	-15	0.375	2.58	40	15	0.5	1.705	35	45	0.1115	0.6905
0	-40	0.3625	0.203	-45	-10	0.478	2.705	45	15	0.36	1.97	40	45	0.1095	0.728
5	-40	0.403	0.1315	-40	-10	0.1655	2.735	-45	20	0.628	2.11	45	45	0.103	0.6925
10	-40	0.397	0.135	-35	-10	0.3	2.69	-40	20	0.472	2.15				
15	-40	0.3625	0.25	-30	-10	0.79	2.47	-35	20	0.169	2.065				
20	-40	0.3065	0.385	-25	-10	1.285	2.205	-30	20	0.315	1.875				
25	-40	0.247	0.53	-20	-10	1.85	1.705	-25	20	0.67	1.565				
30	-40	0.203	0.655	-15	-10	2.315	1.155	-20	20	1.085	1.19				
35	-40	0.169	0.76	-10	-10	2.61	0.69	-15	20	1.405	0.795				
40	-40	0.1375	0.815	-5	-10	2.75	0.26	-10	20	1.71	0.42				
45	-40	0.1125	0.815	0	-10	2.825	0.26	-5	20	1.915	0.15				
-45	-35	0.7405	0.1	5	-10	2.805	0.545	0	20	2.08	0.3815				
-40	-35	0.6905	0.14	10	-10	2.705	0.455	5	20	2.085	0.603				
-35	-35	0.597	0.17	15	-10	2.47	0.625	10	20	1.97	0.25				
-30	-35	0.447	0.235	20	-10	2.14	0.94	15	20	1.705	0.345				
-25	-35	0.2565	0.315	25	-10	1.67	1.345	20	20	1.405	0.475				
-20	-35	0.1345	0.405	30	-10	1.265	1.765	25	20	1.065	0.68				
-15	-35	0.3405	0.515	35	-10	0.875	2.235	30	20	0.795	0.86				
-10	-35	0.5125	0.595	40	-10	0.625	2.595	35	20	0.545	1.1				
-5	-35	0.647	0.61	45	-10	0.405	2.815	40	20	0.42	1.32				
0	-35	0.722	0.585	-45	-5	0.405	2.955	45	20	0.295	1.515				
5	-35	0.7405	0.51	-40	-5	0.135	3	-45	25	0.75	1.635				
10	-35	0.708	0.36	-35	-5	0.51	2.905	-40	25	0.6	1.655				
15	-35	0.6405	0.21	-30	-5	0.985	2.75	-35	25	0.365	1.565				
20	-35	0.5345	0.14	-25	-5	1.515	2.455	-30	25	0.1	1.385				
25	-35	0.425	0.315	-20	-5	2.095	1.955	-25	25	0.33	1.135				
30	-35	0.3315	0.5	-15	-5	2.515	1.42	-20	25	0.65	0.805				
35	-35	0.2565	0.67	-10	-5	2.78	0.875	-15	25	0.885	0.47				
40	-35	0.1875	0.765	-5	-5	2.945	0.397	-10	25	1.235	0.15				
45	-35	0.147	0.82	0	-5	3.03	0.18	-5	25	1.42	0.28				
-45	-30	0.71	0.17	5	-5	2.955	0.51	0	25	1.54	0.49				
-40	-30	0.6	0.225	10	-5	2.795	0.575	5	25	1.52	0.68				
-35	-30	0.43	0.32	15	-5	2.565	0.765	10	25	1.445	0.205				
-30	-30	0.225	0.44	20	-5	2.25	1.095	15	25	1.25	0.28				
-25	-30	0.18	0.58	25	-5	1.75	1.625	20	25	1.04	0.35				
-20	-30	0.445	0.705	30	-5	1.28	2.14	25	25	0.835	0.49				
-15	-30	0.68	0.82	35	-5	0.875	2.595	30	25	0.635	0.65				
-10	-30	0.9	1	40	-5	0.58	2.89	35	25	0.46	0.805				
-5	-30	1.065	1.08	45	-5	0.405	3.11	40	25	0.335	0.96				
0	-30	1.15	1.085	-45	0	0.445	3.205	45	25	0.25	1.1				
1	-30	1.155	0.985	-40	0	0.11	3.24	-45	30	0.805	1.115				
2	-30	1.165	0.815	-35	0	0.43	3.11	-40	30	0.705	1.135				
3	-30	1.165	0.58	-30	0	1.055	2.945	-35	30	0.525	1.155				
4	-30	1.17	0.335	-25	0	1.635	2.655	-30	30	0.315	1.165				
5	-30	1.18	0.115	-20	0	2.235	2.235	-25	30	0.115	1.18				
6	-30	1.165	0.315	-15	0	2.655	1.635	-20	30	0.335	1.17				
7	-30	1.155	0.525	-10	0	2.945	1.055	-15	30	0.58	1.165				
8	-30	1.135	0.705	-5	0	3.11	0.43	-10	30	0.815	1.165				
9	-30	1.115	0.805	0	0	3.24	0.11	-5	30	0.985	1.155				
10	-30	1.1	0.25	5	0	3.205	0.445	0	30	1.085	1.15				
15	-30	0.96	0.335	10	0	3.11	0.405	5	30	1.08	1.065				
20	-30	0.805	0.46	15	0	2.89	0.58	10	30	1	0.9				
25	-30	0.65	0.635	20	0	2.595	0.875	15	30	0.82	0.68				
30	-30	0.49	0.835	25	0	2.14	1.28	20	30	0.705	0.445				
35	-30	0.35	1.04	30	0	1.625	1.75	25	30	0.58	0.18				
40	-30	0.28	1.25	35	0	1.095	2.25	30	30	0.44	0.225				
45	-30	0.205	1.445	40	0	0.765	2.565	35	30	0.32	0.43				
-45	-25	0.68	1.52	45	0	0.575	2.795	40	30	0.225	0.6				
-40	-25	0.49	1.54	-45	5	0.51	2.955	45	30	0.17	0.71				
-35	-25	0.28	1.42	-40	5	0.18	3.03	-45	35	0.82	0.147				
-30	-25	0.15	1.235	-35	5	0.397	2.945	-40	35	0.765	0.1875				
-25	-25	0.47	0.885	-30	5	0.875	2.78	-35	35	0.67	0.2565				
-20	-25	0.805	0.65	-25	5	1.42	2.515	-30	35	0.5	0.3315				
-15	-25	1.135	0.33	-20	5	1.955	2.095	-25	35	0.315	0.425				
-10	-25	1.385	0.1	-15	5	2.455	1.515	-20	35	0.14	0.5345				
-5	-25	1.565	0.365	-10	5	2.75	0.985	-15	35	0.21	0.6405				
0	-25	1.655	0.6	-5	5	2.905	0.51	-10	35	0.36	0.708				
5	-25	1.635	0.75	0	5	3	0.135	-5	35	0.51	0.7405				
10	-25	1.515	0.295	5	5	2.955	0.405	0	35	0.585	0.722				
15	-25	1.32	0.42	10	5	2.815	0.405	5	35	0.61	0.647				
20	-25	1.1	0.545	15	5	2.595	0.625	10	35	0.595	0.5125				
25	-25	0.86	0.795	20	5	2.235	0.875	15	35	0.515	0.3405				
30	-25	0.68	1.065	25	5	1.765	1.265	20	35	0.405	0.1345				
35	-25	0.475	1.405	30	5	1.345	1.67	25	35	0.315	0.2565				
40	-25	0.345	1.705	35	5	0.94	2.14	30	35	0.235	0.447				
45	-25	0.25	1.97	40	5	0.625	2.47	35	35	0.17	0.597				
-45	-20	0.603	2.085	45	5	0.455	2.705	40	35	0.14	0.6905				
-40	-20	0.3815	2.08	-45	10	0.545	2.805	45	35	0.1	0.7405				
-35	-20	0.15	1.915	-40	10	0.26	2.825	-45	40	0.815	0.1125				
-30	-20	0.42	1.71	-35	10	0.26	2.75	-40	40	0.815	0.1375				
-25	-20	0.795	1.405	-30	10	0.69	2.61	-35	40	0.76	0.169				
-20	-20	1.19	1.085	-25	10	1.155	2.315	-30	40	0.655	0.203				
-15	-20	1.565	0.67	-20	10	1.705	1.85	-25	40	0.53	0.247				
-10	-20	1.875	0.315	-15	10	2.205	1.285	-20	40	0.385	0.3065				
-5	-20	2.065	0.169	-10	10	2.47	0.79	-15	40	0.25	0.3625				
0	-20	2.15	0.472	-5	10	2.69	0.3	-10	40	0.135	0.397				

Figure 12: Combination of $v_1(x, y)$ and $v_2(x, y)$.

4. Conclusion

In this study, voltage transmission between two PS-Inductors were investigated and we made clear to be able to construct the position detection system.

When two same PS-Inductors were matched and frequency was changed, very interesting phenomenon of voltage transmission efficiency was observed. When frequency was around 11.7[MHz], maximum voltage transmission efficiency was able to be generated. The maximum output voltage of the input voltage was generated seven times.

Further, voltage transmission efficiency between primary and secondary PS-Inductors was investigated when each diameter was $D = 23[mm],\ 46[mm],\ 69[mm]\ and\ 92[mm]$. Six phenomena were observed.

When the secondary inductor is rotated 180 degrees and the diameter of secondary inductor equals 46[mm], a position of secondary PS-Inductor was able to be detected by measuring $v_1(i, k)$ and $v_2(i, k)$.

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