Performance Improvement of Resonator-Coupled Wireless Power Transfer System Using Dual-Spiral Resonator with Angular Misalignments

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Abstract

The power transmission efficiency of a resonator-coupled wireless power transfer (RC-WPT) system with some angular misalignments is examined in this paper. In addition to conventional single-spiral resonators, the dual-spiral resonators which we have proposed are used in the RC-WPT system. It was confirmed that the power transmission efficiency of the RC-WPT system decreased with the increment of angular misalignments. However, it was shown that the decayed power transmission efficiency due to the angular misalignments could be recovered by adding the appropriate axial displacements between transmitting (Tx) and receiving (Rx) units.

1. Introduction

Wireless power transfer (WPT) systems have become widely employed due to their free access to the power supply. The most popular wireless power transfer system at this time is the electromagnetic-induction type, such as the Qi system used to charge mobile phones. However, that system requires careful positioning and is restricted to short-distance power transmission use. On the contrary, the resonator-coupled type of wireless power transfer (RC-WPT) system [1] has tremendous potential for the layout-free electric power supply for some electric appliances and/or IoT systems in the near future, due to its superiority of efficient power transmission for the middle-range distances [2-4].

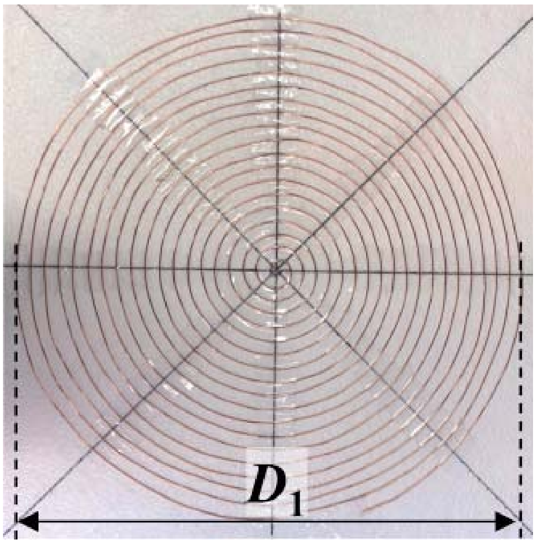

Figure 1a. A conventional single-spiral resonator with 10.0 mm-pitch winding.

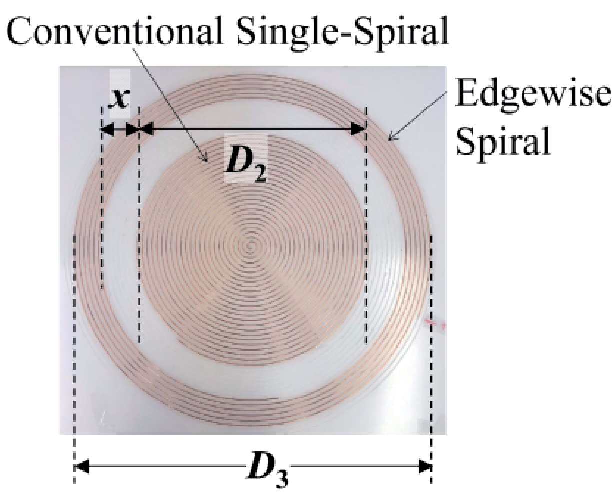

Figure 1b. A dual-spiral resonator with 5.0 mm-pitch winding.

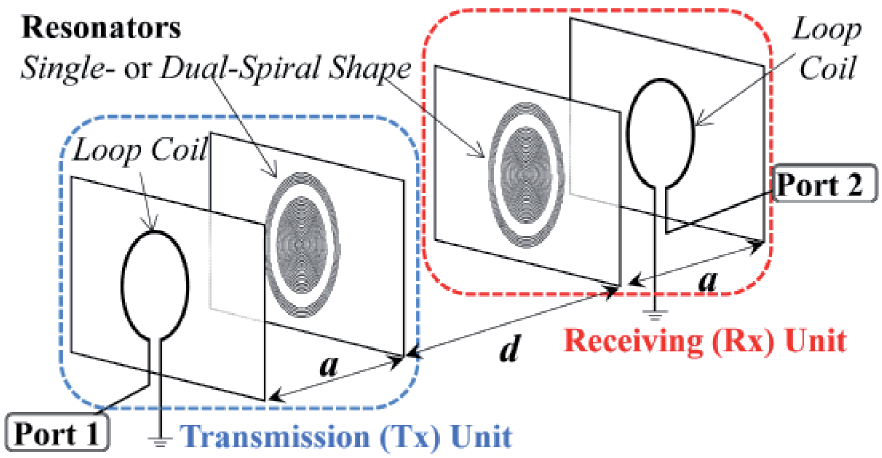

Figure 2. The schematic of the setup of the RC-WPT system.

In order to obtain good performance of an RC-WPT system, two types of spiral resonators have been used throughout this research, making a comparison between them. Up to now, the conventional single-spiral resonators, as shown in Figure 1a, were used for our RC-WPT system. In addition, to realize a widely applicable RC-WPT system, we have proposed the dual-spiral resonators presented in Figure 1b. These can avoid the influence of lossy objects that exist throughout the power transmission path [1, 5].

However, even if the RC-WPT system is used, the decay of transmission power caused by angular misalignments between transmitting (Tx) and receiving (Rx) units is inevitable. In this paper, the decay of the power transmission efficiency for the RC-WPT system with angular misalignments was investigated in detail. A way was found to recover that performance degradation by choosing appropriate positioning of the receiving units.

2. Configuration Setup of RC-WPT System

The schematic setup of our RC-WPT system is shown in Figure 1. Each transmitting and receiving unit consisted of a spiral resonator and a loop coil [6]. The loop coils worked as the power suppliers and receivers of this system, while the spiral resonators electromagnetically coupled between the transmitting and receiving units [3, 4]. Here, the distance between the spiral resonator and the loop coil was set as a [cm], and the distance between the spiral resonators was d [cm], which are also shown in Figure 2.

The loop coil was fabricated on Styrofoam boards using 1.0 mm diameter Cu wire with a loop diameter of 17.5 cm. The ends of the loop coils in the transmitting and receiving units were connected to ports 1 and 2 of vector network analyzer (VNA), respectively. For the initial position, the spiral resonators were facing each other with opposite winding directions, and their center axes coincided including the loop coils when the whole system was observed from the transmitting to the receiving unit [6, 7].

For the resonators in this paper, we used two types of spiral resonators: single-spiral and dual-spiral resonators. The single-spiral resonator was fabricated on Styrofoam boards with a thickness of 1.0 cm, with the 1.0 cm winding pitched spiral-shaped Cu wire, the diameter of which was 1.0 mm, as presented in Figure 1a. The whole diameter of the conventional single-spiral resonator, D_1, was 37.6 cm. For these conditions, the resonator frequency of that single-spiral resonator was just 10.0 MHz. This single-spiral resonator was a kind of spiral coil, so that it formed a strong magnetic field. This structure was of a planar type, so it would be a compact system towards the transmission direction.

Concerned with the resonator, we used dual-spiral resonators that were a combination of the conventional single-spiral and the edgewise-spiral resonators, as shown in Figure 1b. The dual-spiral resonators were fabricated by using polyethylene (PE) substrates with a thickness of 2.0 mm on which a 5.0 mm-pitched spiral-shape groove was drawn, and the 1.0 mm diameter Cu wire was embedded along there. The reason why the dual-spiral resonators were investigated was because it has been clarified that by using dual-spiral resonators, the power transmission efficiency of the RC-WPT system was made insensitive to lossy objects existing on the power transmission path, compared to an RC-WPT system with the conventional single-spiral resonators [1].

The dual-spiral resonators had two resonant points, since they were a combination of two different types of resonators, as mentioned above [5]. As can be seen in Figure 3, we call the resonant mode at the lower frequency *Mode* 1, and the other resonant mode *Mode* 2, respectively. In this study, we set the resonant frequency of *Mode* 1 as 10.0 MHz. For these conditions, the structural parameters of the dual-spiral resonator shown in Figure 2b were $D_2 = 24.1$ cm, $D_3 = 38.6$ cm, and $x = 5.0$ cm. Here, the resonant frequency of *Mode* 2 was 12.9 MHz.

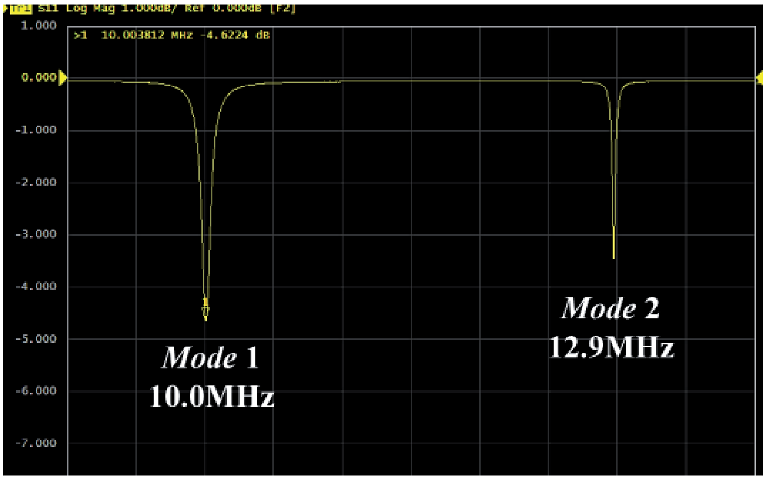

Figure 3. Two resonance points of the dual-spiral resonator.

3. Measurement of Power Transmission Efficiency for RC-WPT System

3.1 Unloaded Q of Dual-Spiral Resonator

At first, to investigate the properties of the single-spiral and dual-spiral resonators, the unloaded Q values, Q_u, which are proportional to the inverse of the losses dissipated in the resonator for *Mode* 1 and *Mode* 2 of the dual-spiral resonator as a function of the distance between the loop coil and resonator, *a,* are presented in Figure 4.

In each resonator, as the distance a is short, the value of unloaded Q becomes small. Here, the unloaded Q indicates the inverse of the loss for the resonator itself, which was isolated from the rest of the circuit. When the distance between the spiral resonator and the loop coil is too close, it might be affected by the interference effects from the loop coil.

From these results, the Q_u of the single-spiral resonator increased as the distance a became larger. It converged to the maximum value of 810 when the distance a was longer than 15.0 cm. The Q_u for *Mode* 1 increased as the distance a became larger. It converged to the maximum value of around 700 when the distance a was larger than 15.0 cm. To the contrary, the Q_u for *Mode* 2 showed almost the same characteristics when the distance a was shorter than 9.0 cm. However, it decreased when the distance a was larger than 9.0 cm, and could not be measured after the distance a was larger than 12.0 cm. The reason why this phenomenon for *Mode* 2 occurred has not yet been resolved. It could be made clear with the detailed inspection of the modal analysis for *Mode* 2.

3.2 Power Transmission Efficiency of RC-WPT System Without Some Misalignments

To evaluate the transmission efficiency of the RC-WPT system, we first found the sets of distances a and d

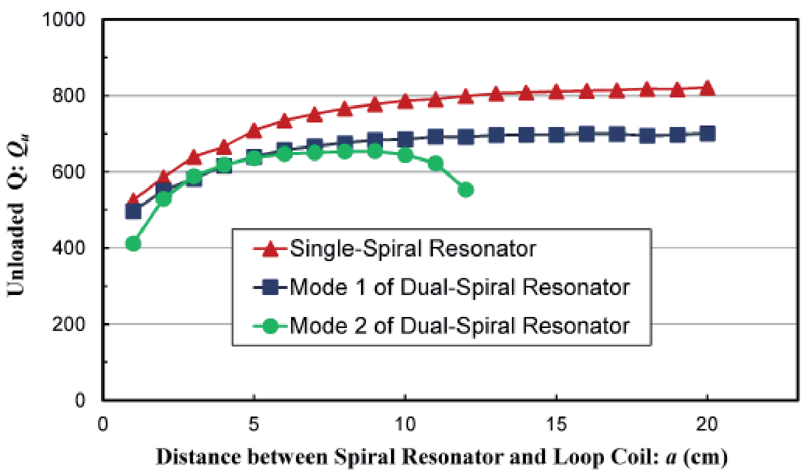

Figure 4. The measured unloaded Q.

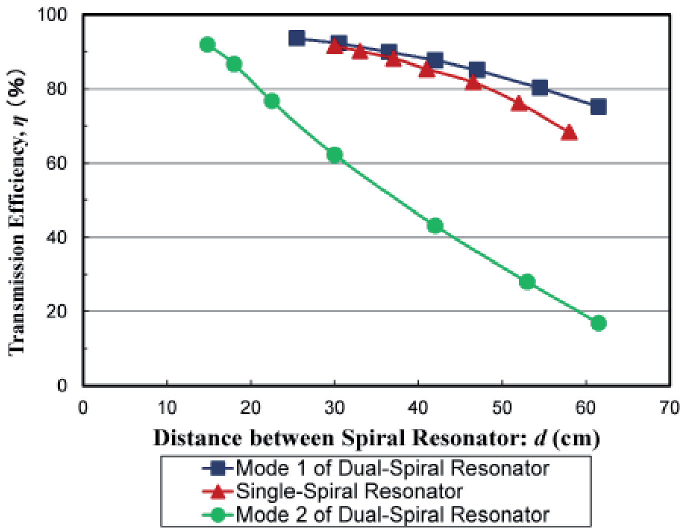

Figure 5. The results for the transmission efficiency of the fabricated RC-WPT system.

that satisfied the matching condition [7]. By choosing the set of a and d under the matching condition, after some fine adjustment of the distance d was carried out, the maximum power transmission efficiency could be measured. The measured results are shown in Figure 5.

From the experimental results, a comparison between the characteristics of the transmission efficiencies indicated that the transmission efficiency of the wireless power transfer system using *Mode* 1 of the dual-spiral resonator was larger than that of the system using the single-spiral and *Mode* 2 of the dual-spiral resonators. In addition, the RC-WPT system with the dual-spiral resonators had a wider transmittable range of d than that of the single-spiral resonator.

The system matching conditions for the RC-WPT system with the dual-spiral and the single-spiral resonators were different. Furthermore, the dual-spiral and the single-spiral resonators were kinds of coil type resonators, and the dual-spiral resonator more tightly confined the electric field to itself compared with the single-spiral resonator, as mentioned in Section 2. The near field of the dual-spiral resonator where the magnetic field dominantly performed would thus differ from that of the single-spiral resonator. At this time, the authors assume that these differences are the reasons why the transmission efficiency of the RC-WPT system with the dual-spiral resonators presented better performance than the system with single-spiral resonators.

3.3 Power Transmission Efficiency of RC-WPT System with Some Misalignments

To examine these circumstances, the structure of the RC-WPT system with angular misalignment was constructed, as shown in Figure 6a. The angular misalignment, θ [°], was defined by the angle between the loop coil's surface in the transmitting unit and the spiral resonator's surface in the receiving unit [6]. The receiving unit was rotated by θ on the transversely center axis of the spiral resonator in the receiving unit. In addition, when

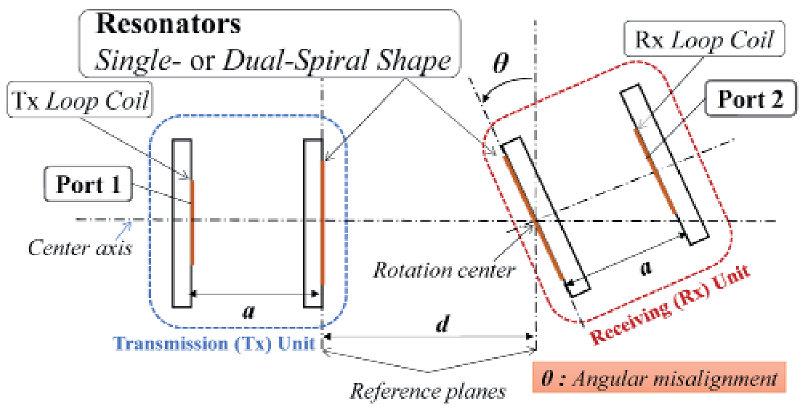

Figure 6a. A top view of the RC-WPT system with angular misalignments but no axial displacement, $c = 0$ cm.

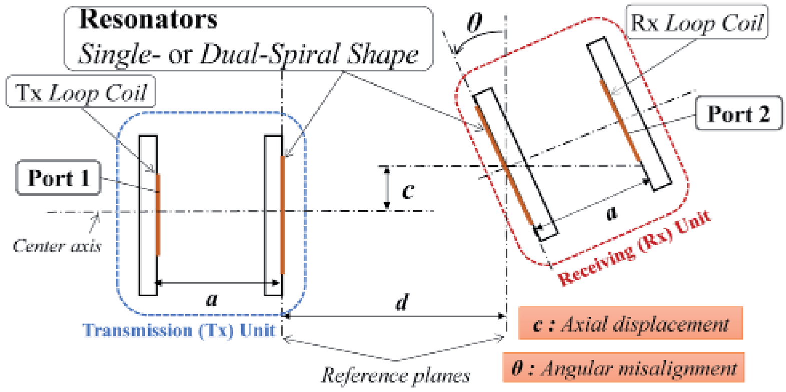

Figure 6b. A top view of the RC-WPT system with angular misalignments and axial displacements.

the spiral coils were observed from transmitting unit to receiving unit, the winding direction of the spiral resonator in the transmitting and receiving units was opposite to each other. The axial displacement between the transmitting and receiving units was set to be *c* [cm]. At first, Figure 6a shows the case for $c = 0$ cm.

As can be seen in Figure 6b, as the decay of power transmission efficiency due to the angular misalignments was investigated, to measure the characteristics of transmission efficiency against angular misalignments in the range of $0° \leq \theta \leq 60°$, the receiving unit was moved towards the reference line by the distance *c*.

Based on the system matching conditions described in [3], to get the maximum power transmission efficiency of the RC-WPT system the appropriate power transmission distance *d* should be chosen for the distance between the loop coil and spiral resonator *a*.

Figure 7 shows the power transmission efficiency of the RC-WPT system as a function of angular misalignments with the hollowed blue squares, □, for *Mode* 1 and the hollowed green circles, ○, for *Mode* 2, when $a = 7.0$ cm and $d = 61.5$ cm. However, the hollowed red triangles, △, for the single-spiral resonators presented the power transmission efficiency as a function of angular misalignments when $a = 7.0$ cm and $d = 58.0$ cm. The difference of *d* against the same *a* is due to the difference of matching conditions of each system since the type of resonators used were not the same. In this paper, we have presented the results of power transmission efficiency of RC-WPT system when $a = 7$ cm only. The results for other combinations of *a* and *d* were also examined, and it was confirmed that they had almost the same tendency and/or characteristics.

From the results in Figure 7, the power transmission efficiency of the RC-WPT system with *Mode* 1 was larger than the *Mode* 2 and single-spiral resonator cases. As the angular misalignments were increased, the power transmission efficiency of the RC-WPT system decayed in each case. It seemed that these decay of the power transmission efficiency of RC-WPT system was caused by the decrease of the overlapping rate between modal

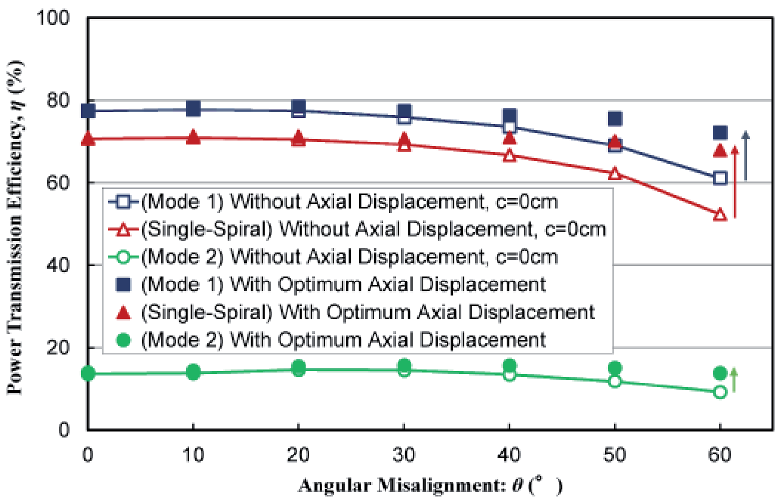

Figure 7. The recovered power transmission efficiency for the RC-WPT system with angular misalignment obtained by choosing the optimum axial displacement where $a = 7.0$ cm.

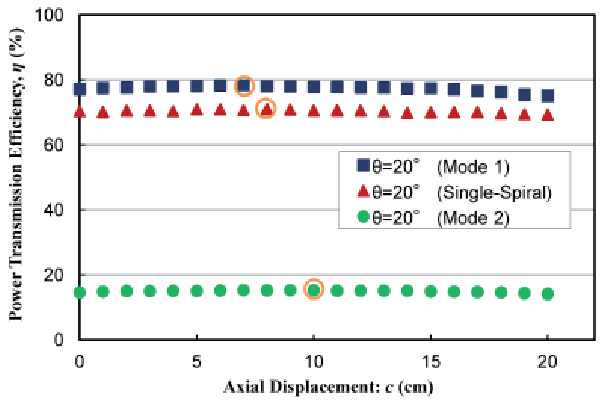

Figure 8a. The relationship between the transmission efficiency and the axial displacement in the case of angular misalignments, $\theta = 20°$.

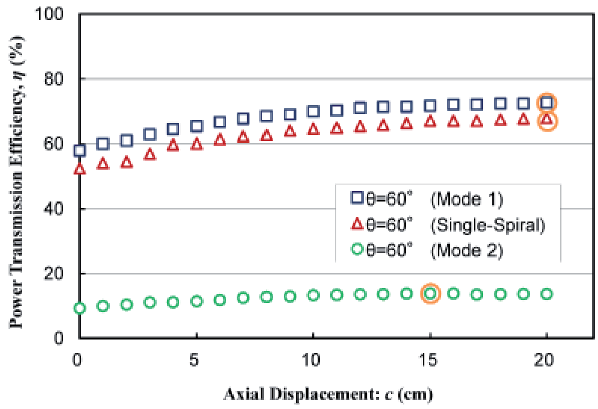

Figure 8b. The relationship between the transmission efficiency and the axial displacement in the case of angular misalignments, $\theta = 60°$.

profiles of the resonators in the transmitting and receiving units due to the tilted receiving unit.

Here, the decay of the power transmission efficiency caused by the angular misalignments could be recovered by adding an appropriate axial displacement. The power transmission efficiency was measured in the case that the receiving units with angular misalignments $\theta = 20°$ (presented in Figure 8a) and for $\theta = 60°$ (presented in Figure 8b) were shifted by a different axial displacement, *c*. Here, the hollowed orange circles, ○ show the axial displacement where the maximum transmission efficiency was obtained. The recovered power transmission efficiencies of the RC-WPT system for choosing the optimum axial displacement against each angular misalignment are also shown in Figure 7 with solid blue squares, ■, for *Mode* 1; with solid green circles, ●, for *Mode* 2 of the dual-spiral resonator; and the solid red triangles, ▲, for the single-spiral resonator. As can be seen in Figure 7, the recovery rate for the RC-WPT system with single-spiral resonators was much larger than that with the dual-spiral resonators. However, the power transmission efficiency for the RC-WPT system using *Mode* 1 of the dual-spiral resonators with a tilted receiving unit was higher than that of the single-spiral resonator. It is obvious that the proposed method for the improvement of the performance of the RC-WPT system with a tilted receiving unit would be effective for the wireless power transfer system with a wide variety of shapes of resonators. In addition, judging comprehensively from these results, the performance against the misalignment between transmitting and receiving units of the RC-WPT system with *Mode* 1 of the dual-spiral resonators is relatively better than the system with single-spiral resonators.

One of authors has presented the result that the transmission efficiency of the butt-joint between optical waveguides through an air gap and between single-mode and multi-mode waveguides greatly depends on the overlapping rate of their modal profile [8, 9]. From these results, the authors assume that by adding the appropriate axial displacement to the tilted receiving unit of the RC-WPT system, the rate of overlapping area between the modal profiles of the transmitting and receiving spiral resonators would become large, so that the decayed power transmission efficiency of the RC-WPT system could be recovered. To confirm these assumptions, we should investigate the modal shape of the spiral resonators in more detail by using an electromagnetic simulator.

4. Conclusions

The power transmission efficiency of the RC-WPT system with angular misalignments of *Mode* 1 was larger than that of the single-spiral and *Mode* 2 systems. In the case of no axial displacement, $c = 0$ cm, as the angular misalignments were increased, the power transmission efficiency of the RC-WPT system was decreased. However, we have experimentally shown that by adding appropriate axial displacement to the tilted receiving unit, the decay of the transmission efficiency of the RC-WPT system due to angular misalignment can be recovered. The recovery rate for *Mode* 1 is also much larger than that of the single-spiral and *Mode* 2 cases. As future research work, the modal properties of the *Mode* 1 and *Mode* 2 cases should be investigated in more detail.

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6. References

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