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Quantification of plate-bending on the mutual coupling capacitance in a capacitive power transfer system

***Abstract*—Capacitive power transfer is near-field wireless power transfer method that offers a promising alternative to power applications prone to bending deformation. Several wireless power transfer applications require a flexible receiver while maintaining high power transfer efficiency and capability. In biomedical applications, for instance, the implanted receiver is often bent to enhance the biocompatibility and minimize the foreign body sensation. Although capacitive power transfer has the potential to charge these applications over short distances, the impact of bending deformation on the capacitive link of a capacitive power transfer system is almost unexplored in literature. This work addresses this knowledge gap by investigating and quantifying the influence of transmitter, receiver and symmetrical bending on the pi-model capacitances along two different bending directions. Understanding the effects of bending on the capacitive link is essential to estimate the true potential of CPT in applications susceptible to bending.**

***Index Terms*—Capacitive power transfer, Non-planar, Bending deformation, Pi-model, Capacitive coupling.**

I. Introduction

Capacitive power transfer (CPT) is an alternative near-field wireless power transfer (WPT) method to the more established inductive power transfer (IPT). While IPT uses the magnetic field to transfer energy wirelessly, CPT relies on the electric field. Compared to IPT, CPT offers several advantages, including a reduction in eddy current power loss, lower electromagnetic field emissions, some transmitter-receiver misalignment tolerance, and the ability to transfer energy through metal surfaces. These advantages make CPT systems an attractive powering method for certain applications such as rotary, underwater and biomedical applications [1]–[3].

In biomedical applications, including implantable medical devices and prosthesis, a flexible implantable receiver is preferred to increase the biocompatibility and minimize the foreign body sensation of the patient [4]. When using an IPT system to power these devices, the bending or deformation of the receiver reduces the mutual inductance [5]–[7]. This reduction lowers the power transfer efficiency and limits the maximum power transfer capability due to the defined guidelines and regulations on electromagnetic field exposure [8], [9].

According to literature CPT systems have a larger misalignment tolerance compared to IPT and are also more robust to other non-ideal conditions such as plate deformation and bending [10], [11]. These characteristics make CPT an interesting alternative for applications requiring a flexible structure such as subcutaneous biomedical implants and prostheses. While the effect of bending on IPT systems is well studied [6], [12], [13], the effect of bending a capacitive coupling structure is almost unexplored. To the best of the authors' knowledge, the effect of bending deformation on a CPT system is reported twice in literature. Fang L. et al. [11] designed a flexible CPT system and studied the effect of symmetrical inward and outward plate bending for moderate bending deformation. In an other paper, Jegadeesan R. et al [14] explored the use of a non-resonance CPT system for subcutaneous implants and described the effect of moderate parallel plate bending deformation for three bending radii. Due to the absence of additional studies about how bending influences the capacitive link, it is impossible to estimate the potential of CPT systems in applications that are susceptible to bending conditions such as biomedical implants, prosthesis, flexible wearable devices, robotic joints etc.

This paper investigates the influence of bending on a typical four plate CPT system. To study the effect of bending, the capacitive link is modeled using the equivalent pi-model (Fig. 1), which includes three coupling capacitances: the mutual coupling capacitance C_M, the primary coupling capacitance C_P and the secondary coupling capacitance C_S. In practical CPT systems, additional leakage capacitors are placed in parallel with the primary and secondary coupling capacitance, mitigating their variability due to bending. For this reason, this work primarily focuses on the mutual coupling capacitance. The main objective is defined as the quantification of the bending influence on the mutual coupling capacitance for various transfer distances, providing knowledge that can be used to estimate the usability of CPT systems in different applications that are susceptible to bending conditions.

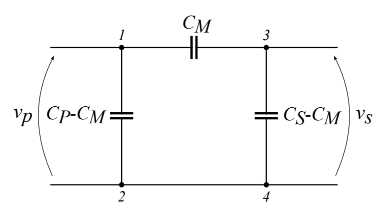


Fig. 1. The equivalent pi-model of a CPT system.

II. Method

To investigate the influence of bending in a typical CPT system, a simulation environment is built in CST-studio electromagnetic simulation software. To validate the reliability of the simulation environment, a planar CPT system is simulated and tested with a corresponding physical system for various transfer distances d. The physical CPT system is built from two identical printed circuit boards (Fig. 2) containing two copper square plates with a plate length of 99 mm and an inter plate gap of 1 mm. For multiple transfer distances the mutual coupling capacitance C_M of the physical planar CPT system is measured using a Hioki IM3536 LCR meter and compared with the simulated mutual coupling capacitance. As shown in Figure 3, the simulated and measured mutual coupling capacitance are in close agreement with each other.

Fig. 2. The physical CPT system built from two identical PCBs.

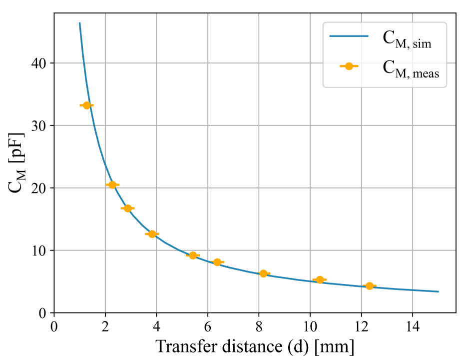


Fig. 3. Comparison between the simulated (blue) and measured (yellow) pi-model capacitances of a planar CPT system.

Using the tested simulation environment, a planar CPT system with a transfer distance of 5 mm is subjected to bending and the effect on the pi-model capacitances is simulated. As stated previously, in biomedical applications this distance corresponds to the distance for a subcutaneous implant, making the set-up directly relevant. To define the degree of bending, both the bending radius and bending angle are considered in this work [1,3]. The bending radius is defined as the radius of the cylinder around which the bent structure is wrapped (Fig. 4(a)). Alternatively the bending angle is defined as the angle between the center and two edges of the bent structure (Fig. 4(b)).

On a planar CPT system, bending can be applied in different directions. This work is restricted to the quantification of bending around two different axes. The first bending direction is defined by the X-axis, which runs across the width of the transmitter and passes through the inter plate gap between the two transmitter plates (Fig. 5(a)). The second bending

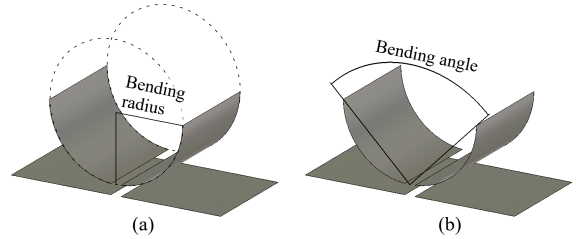


Fig. 4. Definition of the bending using (a) the bending radius and (b) the bending angle.

direction is defined by the Y-axis, an axis perpendicular to the X-axis that crosses the transmitter lengthwise and passes through the center of both transmitter plates (Fig. 5(b)).

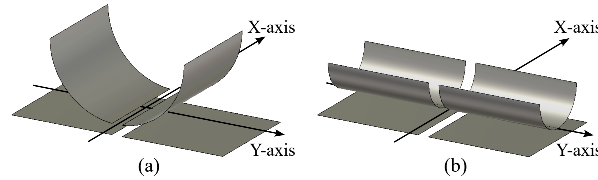


Fig. 5. Definition of the bending along the (a) X-axis and (b) the Y-axis.

Using the two bending axes, different types of bending can be applied to the CPT system. For both axes, we study the influence of three different bending scenarios.

- Transmitter bending: the transmitter (Tx) is bent towards the receiver (Rx). The maximum bending is defined as the bending angle at which the transmitter is just out of reach of the two-plate receiver (Fig.6(a) and Fig.6(b)).
- Receiver bending: the receiver (Rx) is bent away from the transmitter, with a maximum bending angle of 90° (Fig.6(c) and Fig.6(d)).
- Transmitter and receiver bending: both the transmitter (Tx) and receiver (Rx) are bent symmetrical in the same direction. The receiver can reach a maximum bending angle of 90° (Fig.6(e) and Fig.6(f)).

In Fig. 6 the electric field simulations of all six bending scenarios (three for each bending axis) are shown at their maximum bending scenario. In CST-studio the CPT system is drawn as a two port network to simulate the pi-model capacitances. To visualize the electric field, the transmitter port of the two-port network is energized while the receiver port is short-circuited.

III. Results

A. Influence of bending on capacitive link

To quantify the influence of bending on the different pi-model capacitances, the pi-model capacitances obtained at the planar position are considered as a reference. Starting from this situation, the CPT system is bent and the variation in pi-model capacitances is obtained and normalized to their corresponding reference capacitance. In Fig. 7 the influence of X-axis and Y-axis bending on a CPT system with a transfer distance d of 5 mm as a function of the bending radius

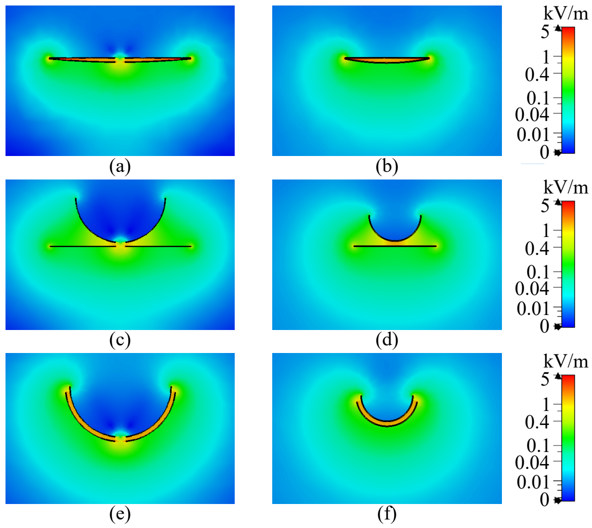


Fig. 6. The simulated electrical field when the receiver is placed above the transmitter and at the maximum bending scenario for (a) Tx X-axis bending, (b) Tx Y-axis bending, (c) Rx X-axis bending, (d) Rx Y-axis bending, (e) Rx&Tx X-axis bending and (f) Rx&Tx Y-axis bending, with the receiver positioned above the transmitter.

(Fig. 7(a)) and bending angle (Fig. 7(b)) is shown. In both figures the planar reference capacitance is located left on the graph. As the system is bent, both the bending radius and bending angle decrease. Bending the transmitter towards the receiver (blue) increases the mutual coupling capacitance as the average transfer distance d reduces. The opposite occurs when the receiver is bent away from the transmitter (yellow). For symmetrical bending (red) a constant mutual coupling capacitance value is obtained. For small bending radii a slight deviation is observed. This is due to a reduction in the active plate area since the two plate transmitter and receiver are wrapped around a cylindrical shell with different dimensions.

In literature, the bending radius is often used to define the curvature of a bent structure [11], [14]. As shown in Fig.7(a), the effect of bending on the mutual coupling capacitance is only significant for small bending radii. For large bending radii, the mutual coupling capacitance converges to its planar reference value which is located at a bending radius of infinity. The dependency on the system dimensions is a limitation on the bending radius, making this parameter unsuitable to compare the effects of bending across different systems. To define bending curvature independently of the system dimensions, the alternative bending angle can be used. As shown in Fig.7(b), using the bending angle eliminates the asymptotic behavior and sets the reference planar scenario at a bending angle of 180°. For the remainder of this work, the bending angle is used to quantify the bending deformation.

Similar to the mutual coupling capacitance, the influence of bending on the primary (dashed line) and secondary coupling capacitances (dotted line) can be studied (Fig. 8). For all X- and Y-axis bending scenarios considered in this work, the influence of bending on the primary coupling capacitance is identical to its influence on the secondary coupling capacitance. In a typical CPT system additional leakage capacitances are placed in parallel to these capacitances to reduce the size of the inductance of the compensation network. As a result the variations in primary and secondary coupling capacitance will be reduced. Nevertheless, the occurrence of large variations in these capacitances could still affect the overall performance of the CPT system.

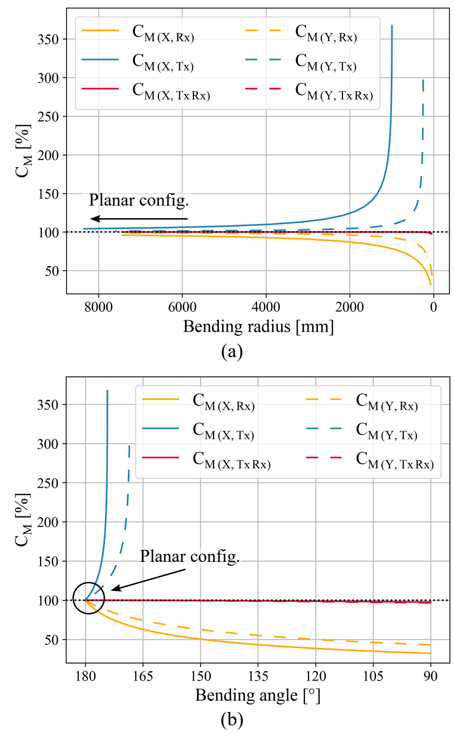


Fig. 7. The influence of X-axis (full line) and Y-axis (dashed line) bending on the normalized mutual coupling capacitance C_M in function of (a) the bending radius and (b) the bending angle.

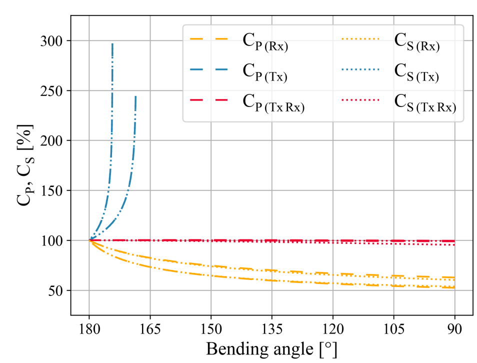
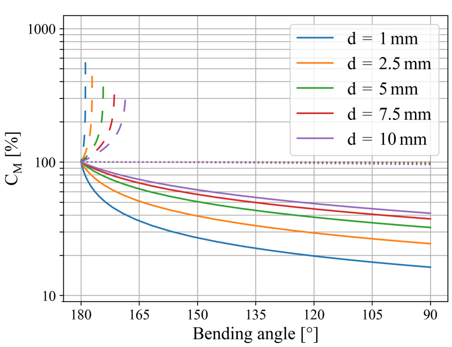


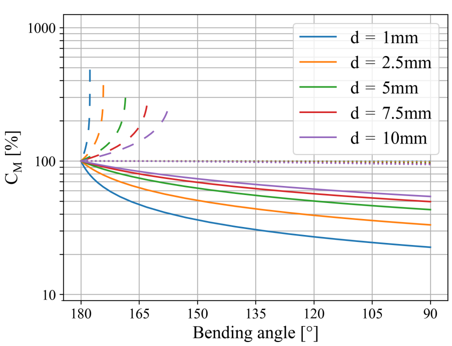
Fig. 8. The influence of bending on the normalized primary (dashed line) and secondary (dotted line) coupling capacitance.

B. Influence of the transfer distance

Bending the two-plate transmitter or receiver in a CPT system changes the average power transfer distance. The relationship between the bending angle and the pi-model capacitances (Fig. 7, Fig. 8) indicates that the impact of bending on the pi-model capacitances is significant for small average transfer distance and decreases as the average transfer distance increases. This suggests that the found correlation between the bending angle and pi-model capacitances should also depend on the initial planar transfer distance (d). To validate this hypothesis, the effect of bending on the mutual coupling capacitance for a planar transfer distance of 1, 2.5, 5, 7.5 and 10 mm for all six bending scenarios is simulated (Fig. 9). For both transmitter or receiver bending the effect of bending on the mutual coupling capacitance decreases as the initial planar plate distance increases. In the case of symmetrical bending, the influence of bending is negligible and corresponds with the reference planar capacitance regardless of the planar transfer distance and the degree of bending. For large bending angles a slight decrease in mutual coupling capacitance is found and increases with increasing transfer distance. This occurs because the transmitter receiver plate overlap decreases at large bending angles, since the bending radius of the transmitter is larger than that of the receiver.



(a)



(b)

Fig. 9. The influence of (a) X-axis and (b) Y-axis bending on the normalized mutual coupling capacitance for a transfer distances of 1, 2.5, 5, 7.5 and 10 mm.

IV. Conclusion

According to literature CPT is an interesting alternative to wireless power applications that require a flexible coupling structure over a short transfer distance. Biomedical applications, for instance, require a flexible receiver to increase the biocompatibility and reduce the foreign body sensation. To estimate the usability of CPT to power applications susceptible to bending, this paper investigates and quantifies the impact of bending on the pi-model capacitances. For symmetrical transmitter and receiver bending, no significant deviation in pi-model capacitances is found, regardless of the imposed bending angle. Single transmitter or receiver bending, affects the average transfer distance and pi-model capacitance of the CPT system. Bending the transmitter towards the receiver, increases the average transfer distance and mutual coupling capacitance. The opposite occurs when the receiver is bent away from the transmitter. The influence of bending on the mutual coupling capacitance also depends on the planar transfer distances. We found that when the planar transfer distance increases, the impact of bending on the pi-model capacitances decreases for single transmitter or receiver bending.

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