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Wireless actuation within hermetically enclosed precision systems

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Abstract

High-precision devices, such as mass comparators and nanofabrication machines investigated at Technische Universität Ilmenau, have achieved astonishing performances with current resolutions in the nano-newton and subnanometer-range, respectively. The further improvement of these systems requires the elimination or, at least, the minimization of any possible source of error, which is partially accomplished by placing them in hermetically closed chambers under controlled environmental conditions up to vacuum. However, processes inside the chamber also generate disturbances to the environment and adjacent subsystems. Fine adjustment systems are commonly operated and controlled remotely using electric current as the carrier. The energy and signal transfer through electric cable connections comes with a number of disadvantages such as the generation of heat and electromagnetic fields, the introduction of mechanical forces and moments, the release of gas or even solid particles, among others. Due to their unstable and nonlinear character, these side effects are not always possible to quantify and compensate. The present contribution evaluates wireless power transfer methods as an alternative for supplying power to fine adjustment systems. The side effects of power transfer methods are evaluated and compared using analytical models. Based on the results, a systematic evaluation leads to the selection of actuator principles for the synthesis of a wireless actuator with strongly reduced side effects inside enclosed precision systems.

Keywords: wireless power transfer, actuators, hermetically closed environments, side effects

1. Introduction

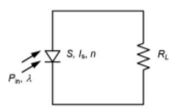
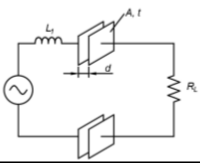
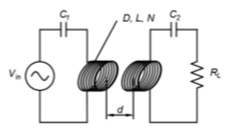
To maximize the performance of high-precision devices, such as mass comparators [1] and nanofabrication machines [2], they are usually placed in hermetically closed chambers under highly controlled environmental conditions up to vacuum. Still, the systems within the chamber interact negatively with each other or affect the environmental conditions. In this context, remotely controlled fine adjustment systems gain particular importance since they are used in units that are highly influential to the device function. The energy transfer through electric cables produces various side effects. The generation of heat and electromagnetic fields, the introduction of restoring forces and moments due to the cable stiffness, and the release of gases trapped in the insulation material need to be mentioned primarily. Due to their unstable and nonlinear character, the compensation of these effects is not always possible, thus, limiting the achievable degree of precision of the device.

For the further improvement of precision systems, there is a need to minimize the aforementioned effects. This contribution evaluates the use of wireless power transfer (WPT) methods to overcome the limitations of electric cables in fine adjustment systems used in enclosed precision systems. Emphasis is placed on the determination of the side effects of the different WPT methods and the selection of suitable principles for developing a wireless actuator with strongly reduced side effects.

2. Wireless power transfer

WPT methods enable the transfer of energy without the need for a solid connection between the source (transmitter) and the load (receiver). As such, the permanent mechanical coupling due to the electric cable is eliminated. WPT systems are classified in [3-6]: acoustic, capacitive, inductive, optical, and microwave. Their design is mostly based on the power requirements and on the distance between transmitter and receiver.

Table 1 Parameters of the WPT systems

WPT System	Parameters
Optical 	Power $P_{\text{in}} = 10$ mW Wavelength $\lambda = 900$ nm Responsivity $S = 0.6$ A/W Saturation current $I_s = 0.1$ nA Quality factor $n = 1.1$
Capacitive 	Input voltage $V_{\text{in}} = 100$ V Frequency $f = 1$ MHz Surface $A = 10$ mm $\times$ 10 mm Thickness $t = 2$ mm Resistivity $\rho = 0.265$ nΩ m Distance $d = 1$ mm
Inductive 	Input voltage $V_{\text{in}} = 100$ V Frequency $f = 1$ MHz Diameter $D = 10$ mm Length $L = 25$ mm Turns $N = 100$ Resistivity $\rho = 0.168$ nΩ m Distance $d = 10$ mm

In this work, three different WPT systems are designed for comparison, as shown in Table 1. Taking into account the implementation in fine adjustment units, the coupling interfaces are kept compact. The side effects at resonance are also evaluated. Resonance is obtained by introducing an additional inductance L_1 in the capacitive system and two capacitances in the inductive system (C_1 in the transmitter and C_2 in the receiver) to compensate the impedance of the interfaces. The heat generation and electromagnetic emissions are described by the heat losses $\dot{Q}$ and the magnetic field B at the interface. The systems are evaluated analytically using circuit theory [7] and compared for different load resistances R_L. For better comparability with the optical WPT through laser, which has non-comparable input parameters, the heat losses per input energy amount $\dot{Q}/P_{\text{in}}$ is calculated.

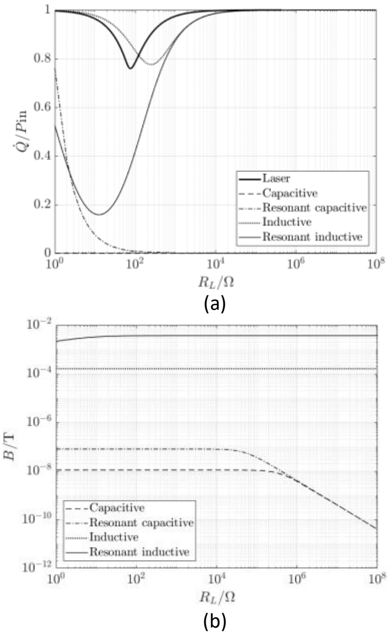


Figure 1. Induced side effects by different WPT methods: (a) heat losses per input energy, (b) magnetic field at the interface.

The results are shown in Figure 1. Laser WPT produces no electromagnetic emissions that would cause electromagnetic interference (EMI) with other devices. However, at least 80% of the introduced energy is transformed into heat due to the low conversion efficiency of photodiodes. The energy losses of the beam inside the chamber can be considered negligible for the intended conditions. Due to its nature, inductive WPT requires a strong magnetic field and produces significant heat losses in the coupling coils. In addition, typical copper wires used for the coils are not suitable for vacuum due to outgassing. When brought to resonance, the system transfers much more power with relatively less heat losses but the presence of a magnetic field limits its application in the targeted high-precision devices. In contrast, capacitive WPT shows significantly smaller side effects. Since there is no dielectric material between the plates or there is only air, dielectric heat losses are assumed to be zero and only ohmic resistance losses are considered. The plate capacitors can also be fabricated of other materials aside copper, like aluminum [5], for their use in vacuum. Still, when working at resonance, higher heat losses are produced due to the compensation inductance. A magnetic field is also produced between the capacitor plates due to the alternating electric field, but its value is significantly lower than in inductive WPT.

Based on the analytical results, an evaluation is conducted to select the most appropriate WPT method for the application in enclosed high-precision systems, which is presented in Table 2. Other design criteria, e.g. required space, are also taken into consideration. Capacitive WPT appears to be the most suitable method regarding the considered side effects. Due to the nature of plate capacitors, the electromagnetic fields are well contained within the metal plates, reducing possible parasitic couplings. Aside from the small heat losses, the required large inductance can be avoided by using other compensation circuit topologies [4]. However, a small capacitive force is produced between the transmitter and the receiver, which would cause vibrations. Another issue is the possibility of a dielectric breakdown, which for air is around 3 kV/mm [8], limiting its use for high-resistive loads. Capacitive WPT is also limited to very small distances, thus, power can only be supplied to static adjustment systems. For long-range applications, such as moving devices, laser WPT is better suited.

Table 2 Evaluation of WPT methods

Method	range	power	space	heat	EMI
Capacitive	-	-	o	++	++
Resonant capacitive	-	+	o	+	+
Inductive	o	-	+	-	--
Resonant inductive	o	+	+	o	--
Optical	++	o	++	-	++

++ very good / + good / o sufficient / - tolerable / -- unsatisfactory

3. Actuator principles

Based on the properties of the WPT methods, possible actuator principles can be selected for the synthesis of a wireless actuator. Due to the limited forward voltage of photodiodes, laser WPT is mainly suited for low voltage applications. The generated current is regulated by the laser power, allowing its use in current-driven actuators, such as electromagnets or magnetostrictive actuators. Another option is the use of thermal actuators, e.g. shape memory alloys (SMA), which can utilize its thermal energy but are less efficient. In comparison, capacitive WPT is better suited for higher voltage loads. Voltage-driven actuators also reduce heat losses since they can work with small currents. For minimizing the side effects of the actuators used in the targeted fine adjustment system, a voltage-driven actuator, e.g. piezoelectric, electrostrictive or electrostatic, supplied using a capacitive WPT system is the most suitable solution.

4. Conclusions

To eliminate the side effects of electric cables for the power supply of actuators in fine adjustment systems used in enclosed precision devices, three different WPT methods are compared regarding the generated heat and magnetic field. Based on the analytical calculations and the technical evaluation, a capacitive WPT system is best suited due to its much lower side effects in comparison to inductive or optical methods. It can also produce higher output voltages, which allows its use for voltage-driven actuators with high efficiency. This principle combination is most suitable for the design of actuators with strongly reduced side effects. However, the transfer range of capacitive WPT is limited to very small distances, usually below 1 mm, and further options need to be evaluated for long-range applications. Among the conceivable possibilities are the use of low-power lasers over long adjustment times, or the implementation of an energy storage system on the device to achieve autonomous operation. Still, further investigation is necessary.

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