Shaped coil-core design for inductive energy collectors

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Abstract

Coil design is important for maximizing power density in inductive energy harvesting as well as in inductive power transfer. In this work, we present a study of coil performance, based on simulated flux distributions corresponding to a real aircraft application case. The use of funnel-shaped soft magnetic cores boosts magnetic flux density by flux concentration and allows the use of a shorter winding perimeter. This reduces the transducer mass as well as the coil resistance (R_{COIL}), thereby increasing the power density. Analysis and simulation shows a fifty-fold power density increase from moderate funneling and another two-fold increase by coil size optimization. Results are compared with experimental measurements presented in [1] which demonstrate a 36 μW/g (106 μW/cm^3) power density from alternating environmental magnetic fields in the 10 μT / 300 Hz range.

Introduction

Inductive energy collection from ambient sources has demonstrated considerable progress in recent years as a method to power wireless sensors [2-5]. Power densities in the range of 0.1-0.5 mW/cm^3 for low current (1 A) [3] and as high as 16 mW/cm^3 from high current (200 A) power lines have already been demonstrated [4]. A key limiting factor in this progress is the requirement for very specific environmental and installation conditions, such as the ability to install a soft-core loop around a given power line, e.g. in a Rogowski coil geometry. Inductive power transfer has progressed even faster, allowing efficient wireless power transfer from a dedicated magnetic field source to a target, at distances similar to the size of the coils used [6]. Very recently, a study of funnel-shaped soft-core geometries has revealed a fifty-fold increase in collected power density, achieved by core-coil mass reduction as well as by the significant reduction of R_{COIL} due to the shorter required winding perimeter for a given total flux Φ[1].

Core Design

The optimized core and coil design approach is described using the magnetic field distribution of a current-carrying structure (Fig.1). If the current is alternating, a coil located in the vicinity of the field experiences varying flux and a voltage is induced allowing the collection of power is possible. Depending on structure size and frequency range, the skin effect may concentrate current flow to the structure edges, thereby enhancing the available magnetic flux density at these locations. Simulation results demonstrating this effect are presented in Fig. 2, using the Comsol finite element modeling suite, for a structural beam carrying a 25 A RMS current at 1 H, 50 Hz, 360 Hz and 1 kHz. The use of funnel-shaped soft-core geometries can be used to guide flux through a small coil cross section. This method has been introduced in [1] and is illustrated in Fig. 3. In this way, the core-coil mass as well as the coil resistance are reduced boosting the achievable power density.

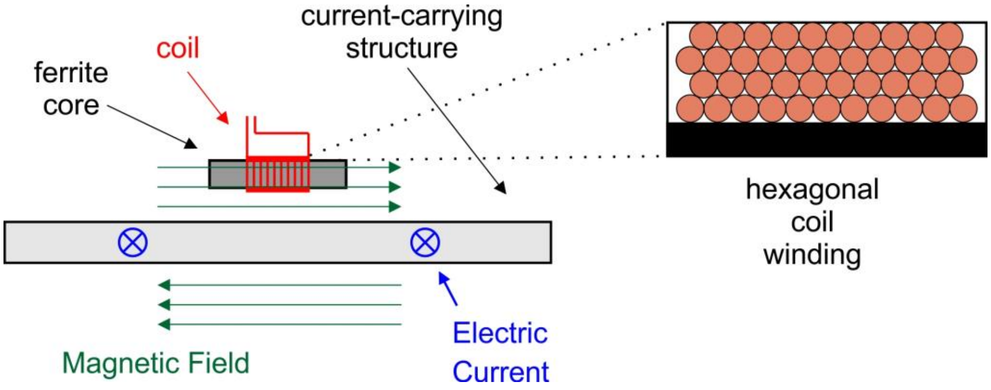

Fig. 1: Left: Concept of operation for inductive harvesting from current-carrying structures. Right: Hexagonal close packed coil winding for coil performance optimization.

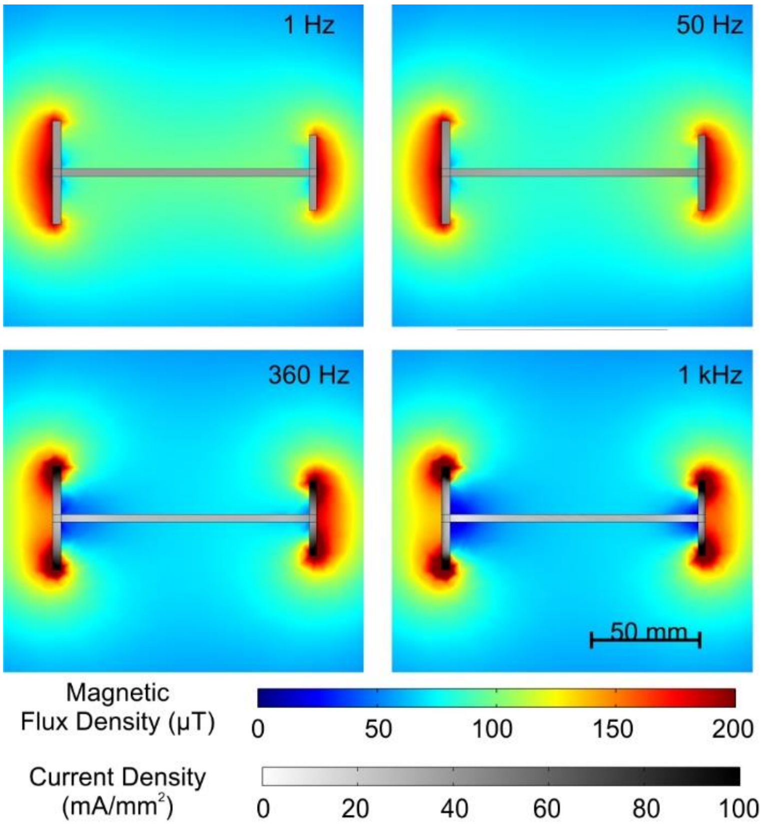

Fig. 2: Simulated 25 A RMS current and field distribution through an aircraft beam use case.

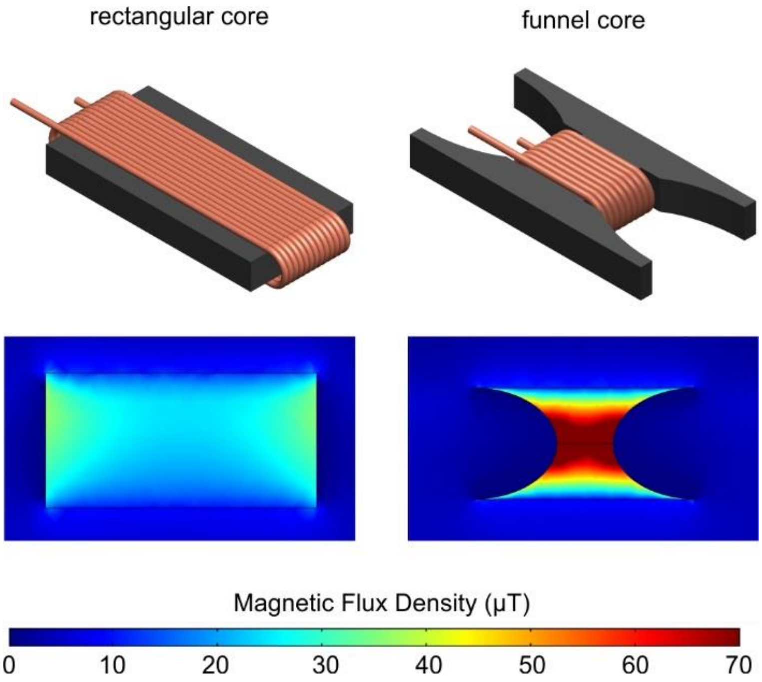

Fig. 3: The concept of flux funneling for higher flux density and smaller winding perimeter. Top: Conceptual illustration of a core-coil system for a rectangular and a funneling geometry. Bottom: Corresponding simulated magnetic flux density.

This effect was studied in [1] by simulating funnel structures of various funneling ratios. The results are presented in Fig. 4. A fifty-fold power density increase is expected for a core with 1:8 funneling ratio in comparison to a core-less coil. Further simulation work has been performed to quantify the role of geometrical dimensions and design detail. The length of the top/bottom horizontal legs of the funneling structure determines the amount of collected flux (Fig.5:top). In contrast, the fillet parts of a funneling structure are not essential, due to the high material/air permeability ratio (Fig.5:bottom), thereby allowing simple H–shaped structures to be used for this method.

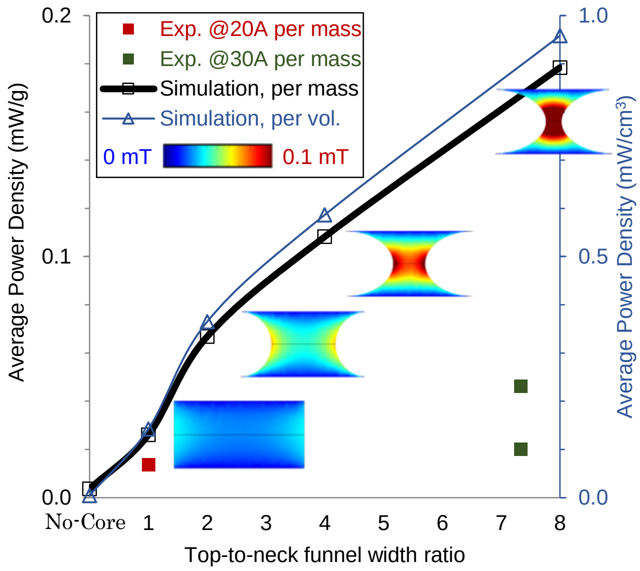

Fig. 4: Simulation and experimental results for a 200 A amplitude, 300 Hz structural current from [4] showing a 50-fold power density increase with using funneling cores in comparison to a coreless coil.

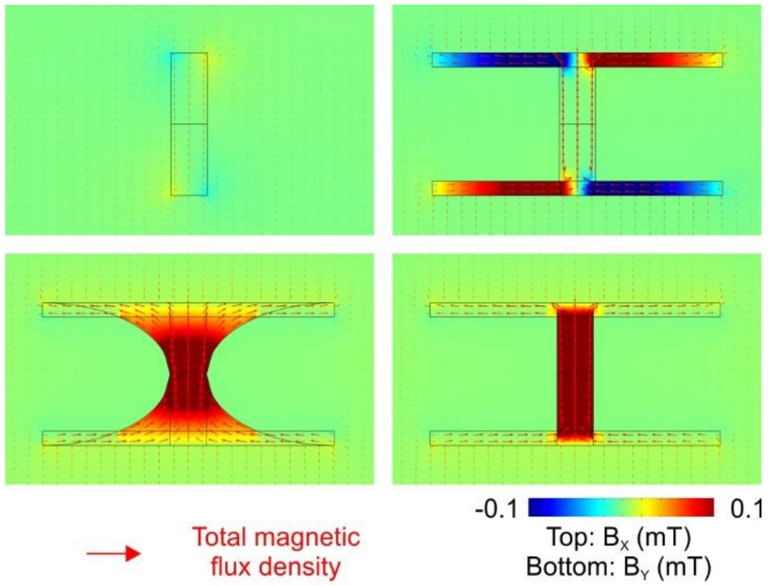

Fig. 5: Visualization of flux highlighting the critical role of the horizontal collector beams (top) and the non-critical role of fillets (bottom), for $\mu_r = 200$.

Coil Design

For a given coil mass, number of turns N and coil wire diameter d, the power output $P = (N \cdot d\Phi/dt)^2/(4 \cdot R_{COIL})$ remains constant regardless of the *N*/*d* selection. The *N*/*d* balance should therefore be selected in order to provide adequate voltage for efficient power management in the expected field intensity and frequency, within practical fabrication limitations. On the other hand, the selection of balance between core and coil mass (or volume) plays a significant role to the power density of the device. For a given N, the power per coil mass increases with decreasing d, but the core-included power density peaks at a certain *d* value. This is illustrated by numerical calculations in Fig.6.

Conclusions and Outlook

The use of funnel-shaped soft magnetic cores can boost the power density of inductive energy harvesters, with expected increased over a factor of 50 for fabrication-practical aspect ratios (e.g. 1:8). At moderate permeability values (~200), structural fillets are not significant, and therefore simple H structures can be employed. Higher permeabilities could allow very thin flux collector beams to be employed. For a given coil mass the number of turns and wire diameter do not affect the power output and should be selected according to voltage level requirements. The core / coil mass balance is important and can be optimized by simple calculation to provide maximum power density. A derivation and detailed analysis of optimal core/coil mass design would be very interesting and useful for any inductive energy collection and transfer systems, including transformers.

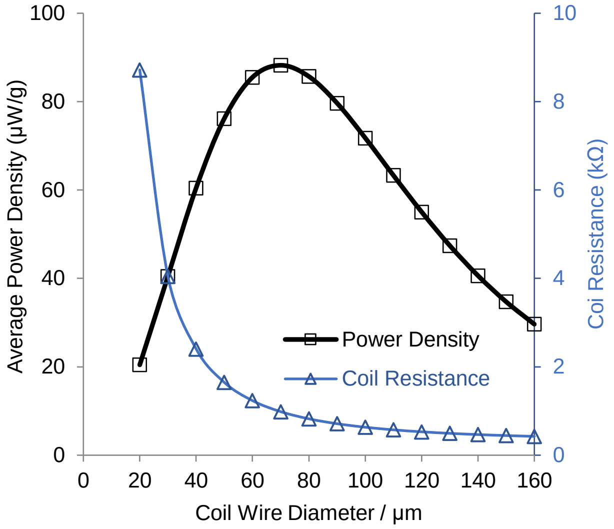

Fig. 6: Power density vs coil size for a 1:8 funnel core, calculated from simulated flux distribution corresponding to a 25 A RMS, 360 Hz current through an aircraft structural beam. This calculation demonstrates that the peak power density occurs at a certain balance between coil and core size or mass.

Acknowledgements

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