Published in IEEE Sensor Letters ©, Volume 3(6), 6001104 (2019) **DOI:** 10.1109/LSENS.2019.2918339

Inductive Energy Harvesting From Current-Carrying Structures

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Received 15 Apr 2019, revised 12 May 2019, accepted 18 May 2019, published ……2019, current version 18 May 2019. (Dates will be inserted by IEEE; “published” is the date the accepted preprint is posted on IEEE Xplore®; “current version” is the date the typeset version is posted on Xplore®).

Abstract— This paper introduces an inductive method for harvesting energy from current-carrying structures. Numerical simulation of a structural beam shows that the skin effect can lead to significant current concentration at edges, providing a five-fold power benefit at such locations, even at frequencies below 1 kHz. The use of a rectangular ferrite core can provide a ×4 power density improvement. The adoption of funnel-like core shapes allows the reduction of core mass and coil frame size, leading to significant further power density enhancement. Magnetic field simulation and coil analysis demonstrate a power density increase of ×49 by ferrite funnels, in comparison to a coreless coil. Experimental results demonstrate rectified power over 1 mW delivered to a storage capacitor, from a 40 × 20 × 2 mm core-and-coil, in the vicinity of a spatially distributed 20 A current at 800 Hz. Rectification and impedance matching are studied experimentally using a voltage doubler circuit with input capacitor tuning to counteract the coil reactance. Experimental results from a spatially distributed 30 A current at 300 Hz and a 1:7 funnel core demonstrate power density of 36 μW/g (103 μW/cm^3), opening up the way to non-invasive inductive powering of systems in the vicinity of current-carrying structures.

Index Terms—Inductive, energy harvesting, current carrier, power line, structures, aircraft.

I. INTRODUCTION

Energy harvesting can provide energy autonomy to wireless sensors, a key engineering requirement for emerging sensing technologies, provided that a suitable environmental source is available at the sensor vicinity. The state-of-art power availability exceeds 0.1 mW/cm^3 from most source types, which is adequate for supporting various wireless sensors at low duty cycle operation, e.g. 1% [1]. However, narrow environmental condition requirements have limited the applicability of energy harvesting to bespoke sensor solutions. A high-priority objective is the development of energy harvesting power supplies, functional over a wider location range. This can be achieved by exploiting energy that is generally available within the internal range of a given sensing application group. For example, vibration of specific characteristics can be expected to be available in the environment of a terrestrial vehicle.

In some vehicles such as aircraft the return current path is common to multiple electrical systems and passes through structural elements, such as beams, rather than cables. This provides a varying magnetic field, available in a wide location range, which could potentially be exploited by inductive, or other magnetic force transducers to power wireless vehicle sensors.

Various methods of energy harvesting from power lines have been proposed in recent years. The employment of a piezoelectric beam with a permanent magnet printed at its tip was proposed in [2] for dual-core, bi-directional power lines. In [3], a similar method is followed, employing a Halbach array of permanent magnets to enhance the resulting magnetic force, and demonstrating 3 mW/cm^3, from a 10 A / 50 Hz power line. An electrostatic approach has been studied in [4] and [5], and a power output of 16 mW from a 0.1 m diameter, 0.2 m long tube, from a 60 kV / 50 Hz power line is reported in [5]. Inductive coupling of a coil-and-core system to the magnetic field of power lines has also been studied [6-9]. A very interesting approach employing a bow-tie shaped core geometry has been reported in [9], showing a ×2.5 increase of power in comparison with a cylindrical core implementation, and demonstrating 0.1 mW/cm^3 from a 11 μT RMS, 50 Hz field. In another very promising implementation reported last year, magnetic core sheet geometries are used as flux guides, demonstrating a power enhancement as high as ×200, and a power output of 1.5 W from a 100 A RMS power line and a credit-card sized coil-and-core device located on the side of the power line core [8]. Inductive power line harvesting on aircraft involves currents of variable frequency in the range up to 800 Hz and has been studied in [7], demonstrating around 0.6 mW/cm^3 using a closed-loop ferrite core around a 0.9 A RMS, 620 Hz power line.

In order to harvest energy from current-carrying structural elements, the spatial current distribution has to be taken into account. The use of mechanical structures with piezoelectric transducers is not advantageous for cases of varying frequency such as in aircraft, because of their requirement for resonant operation. In addition, an electrostatic approach is not possible due to the zero voltage of the return path. In this paper, the potential of inductive energy harvesting from the magnetic field of current-carrying structural elements is studied. The effects of frequency variation, current distribution and field – concentrating magnetic core geometries are evaluated by simulation and experimental results of power availability from spatially distributed currents using inductive coupling and a voltage

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 DOI: 10.1109/LSENS.2019.2918339

doubler circuit are presented. The concept of inductive harvesting from a structural beam current is illustrated in Fig.1. The average power of a coil with loop area A, N turns and resistance R will be:

$$P_{AV} = \frac{V_{rms}^2}{4R} = \frac{V_m^2}{8R} = \frac{(N\Phi_m\omega)^2}{8R} \qquad (1)$$

where V_{rms} is the RMS open-circuit induced voltage, V_m is the open-circuit voltage amplitude while Φ_m and ω are the amplitude and angular frequency of the magnetic flux through A.

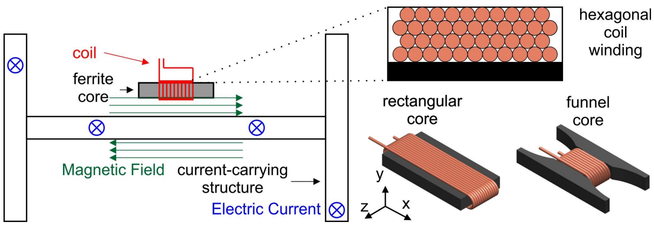

Fig. 1. The concept of inductive harvesting from a current-carrying structure. Coil winding and core shapes are illustrated on the right.

II. THE SKIN EFFECT

The current distribution in a structural beam was studied by finite element analysis using the Comsol software. The beam geometry corresponds to a H-shape structural rail beam of an aircraft, and the simulated material is aluminium. The web width and thickness are 140 mm and 4 mm respectively, while the two flanges are 55 mm and 40 mm wide with 4.5 mm and 3.8 mm thicknesses respectively. A beam length of 1 m was simulated using a current injector and sink located on the outer flat surfaces of each flange. The geometry and current density distribution results are shown in Fig. 2:Top. A total sinusoidal current of 1 A was simulated at 10 Hz (left) and 1 kHz (right). The skin effect pushes current flow to the edges of the beam cross-section leading to significant current concentration at the tips of the flanges, at 1 kHz. This corresponds well with the analytically expected Al skin effect depth of 26 mm at 10 Hz and 2.6 mm at 1 kHz.

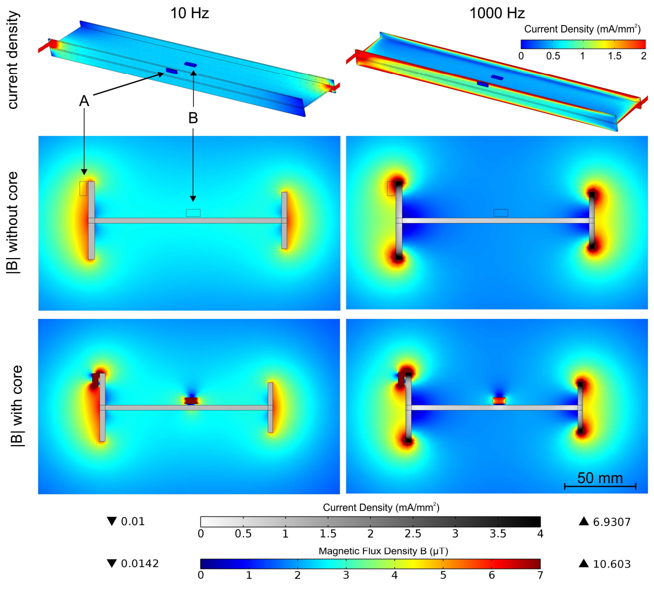

Fig. 2: Comsol simulation of current density J and magnetic flux density B in a structural beam, for 10 Hz (Left) and 1 kHz (Right), 1 A current.

Simulation results of the corresponding magnetic field around the beam are shown in the bottom four plots of Fig. 2, at the cross-section in the middle of the beam length. The current concentration at the beam flange edges results in significant field crowding around the flange tips at 1 kHz. This area is therefore beneficial for determining the optimal location of energy harvesting coil devices.

In order to quantify the skin effect benefit, the total flux available through a 40 × 5 mm frame, with the long size perpendicular to the paper plane and the short axis in the horizontal direction in Fig.2, was calculated at the flange tip (location A) and the web center (location B) of the beam, by integrating the perpendicular magnetic flux density. The resulting flux amplitude as a function of frequency is plotted in Fig. 3 for a total current amplitude of 200 A. A 50% flux increase is observed for the beam tip location, and a 30% flux reduction at the beam center. The corresponding output power assuming a 2500 turn, 0.04 mm diameter Cu coreless coil is also plotted, demonstrating a ×5 power difference between the two installation locations at 1 kHz. The corresponding volume, mass and resistance of the coil are 0.28 cm^3, 2.5 g and 3 kΩ respectively, assuming a 20 mm winding length and a hexagonal close packing. The skin effect benefit can be calculated by comparison with the power scaling with f^2 expected from Faraday's law, plotted as a dashed line in Fig. 3. A benefit of 125% at 1 kHz and 64% at 300 Hz is observed for the side location.

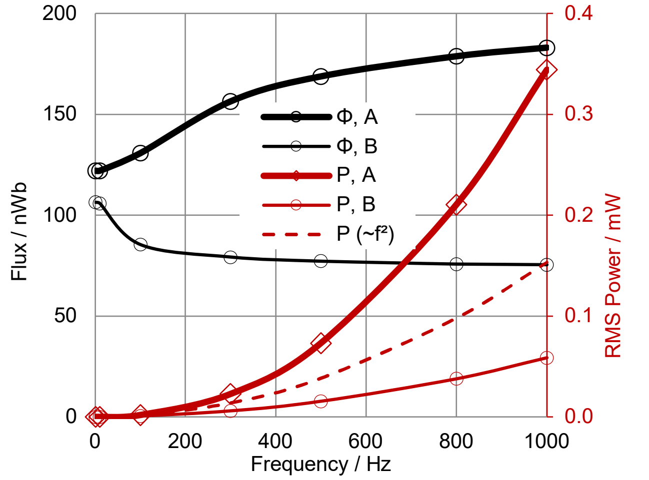

Fig. 3: Simulated flux and power from a 40×5 mm frame at locations A and B in Fig. 2, with a 2500 turn, 0.04 mm Cu wire, from a 200 A current.

III. SOFT CORE GEOMETRIES

In order to enhance the energy harvester power density, a soft magnetic material can be used inside the coil, to increase the magnetic flux density. This effect is illustrated in the simulation results of Fig. 2:Bottom, in which a rectangular 40 × 5 × 20 mm ferrite of $\mu_r = 200$ has been included. The employment of flux-concentrating funnel-like soft-core geometries could allow reduction of the coil cross-section while increasing the total flux. This can reduce the overall device size and mass as well as the coil resistance. To evaluate this effect, the performance of a coil-and-core device using a simple rectangular soft-core block, as shown in Fig. 2 is compared with that of a funnel-like soft-core structure. The two soft core geometries are illustrated in Fig. 4, with flux density distribution results corresponding to a 1A, 1 kHz structure current flow.

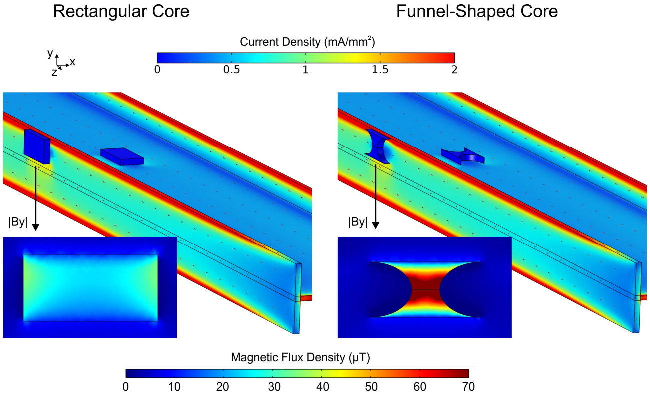

Fig. 4: Simulated current and flux density for two magnetic soft-core geometries, for a 1 A, 1 kHz total structure current.

In order to study the soft-core effect to the power density of the energy harvester, the total flux available through the central 40 × 5 mm frame of the rectangular core and through the 10 x 5 mm frame at the neck of the funnel-shaped core was calculated from the simulated perpendicular magnetic flux density. Results as a function of frequency are plotted in Fig. 5 for a total current amplitude of 200 A, for the two core shapes as well as for a coreless 40 x 5 mm frame. A milder flux dependence with frequency is observed due to the position of the coil frame which is lower than the flange top, where the largest current accumulation occurs. As in the previous section for the skin effect study, the corresponding output power assuming a 2500 turn, 0.04 mm diameter Cu coil with hexagonal close packing is also plotted in Fig. 5.

The six-fold flux increase provided by the rectangular core corresponds to a ×36 increase in power. The funnel structure provides a ×4.5 flux increase but at a much smaller frame, which reduces the coil wire length. The corresponding coil resistance is 1 kΩ, leading to the total power enhancement of ×60 relative to the coreless case, observed in Fig. 5.

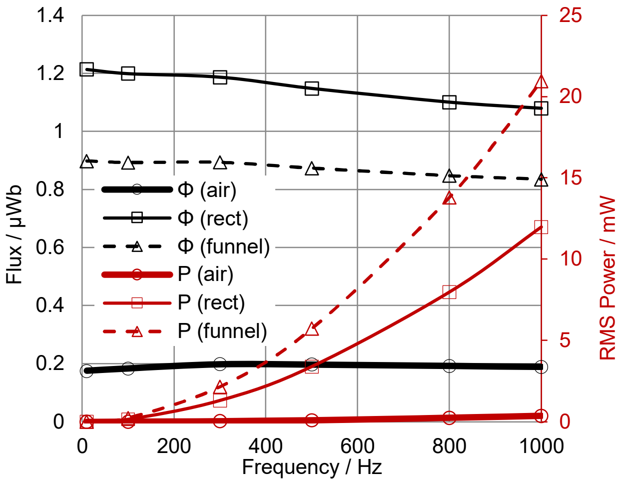

Fig. 5: Simulated flux and power output from a 40 × 5 mm frame without a core, with a rectangular core and with a funnel-shaped core at its 10 x 5 mm neck frame. For the power output calculations, a 2500 turns, hexagonally packed 0.04 mm Cu wire coil is assumed. The structural current amplitude is 200 A.

The benefit of funnel shaped geometries for different width narrowing ratios was evaluated by simulating different geometries and calculating the power output density, assuming the same 2500, 0.04 mm diameter Cu coil. In this study, a double length coil wire was assumed, both for resistance and weight calculations, to account for coil winding practical limitations. The power density was calculated by dividing the output power by the coil and core total mass. The results are shown in Fig 6. The power density increases significantly with increasing top-to-neck width ratio. Magnetic saturation is not limiting the increase due to the low flux density range, up to structural current amplitudes as high as 1000 A for these geometries. In practice, the funneling ratio will be limited by mechanical fragility restrictions. For an 8:1 ratio a four-fold power density increase is achieved, in comparison with a rectangular core, reaching 0.18 mW per core-and-coil gram, or 0.96 mW/cm^3.

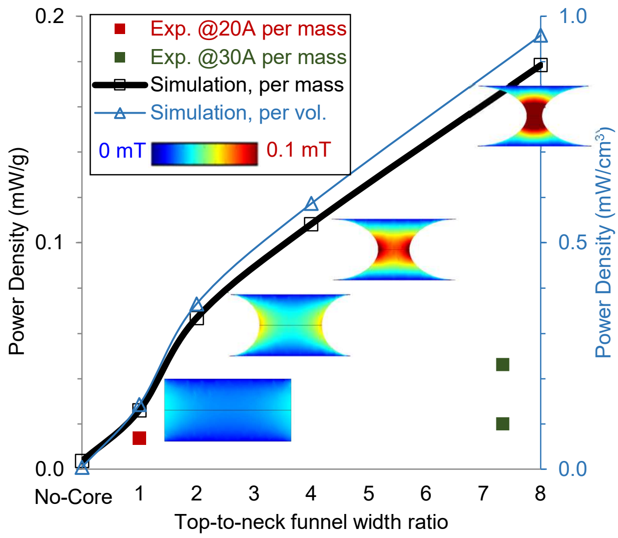

Fig. 6: Calculated power output density as a function of funnel core narrowing ratio, with 2500 turns of a 0.04 mm Cu wire hexagonally distributed around the core neck, for a 300 Hz, 200 A structural current. The flux density distributions are also shown, for a 1 A structural current.

IV. EXPERIMENTAL RESULTS

The possibility of energy harvesting from current carrying structures was evaluated experimentally using a 2500-turns, 40 × 2 mm coil, and a 40 × 2 × 25 mm ferrite core. A spatially-distributed current was emulated using a cable carrying a 1 A current of various frequencies. The cable was passed by the vicinity of the coil-and-core harvesting device 20 times in the same direction, forming loops of a large diameter (indicatively 1 m), and creating a 20 A current distributed over a distance of 25 mm. This corresponds approximately to the 0.2 A/mm^2 current distribution at the 25 × 4.5 mm beam flanges simulated in Sections II and III for a 200 A structural current at low frequencies, at which the skin effect is weak.

The coil is connected to a voltage doubler circuit for rectification and the output power is measured in a load resistor R_L, as shown in the inset of Fig. 7. Schottky diodes were selected to reduce losses. In order to maximize power transfer to the load, R_L must be selected to be equal to the total equivalent impedance of the rest of the circuit. The first capacitor C_t connected in series with the coil can be used to match and cancel the inductive part of the coil output resistance, thereby increasing the power output capability of the system. This effect was studied experimentally by measuring the output power as a function of R_L for different C_t and frequency values. The results are shown in Fig. 7. A maximum power output of 1 mW is obtained from the 800 Hz signal, at resonance and a 5.1 kΩ load. Taking into account the total core-coil mass, this corresponds to an experimental DC power density of 13.7 µW/g, indicated as a red square in Fig. 6. This result is 53% of the simulated AC power output for a 40×5×20 mm rectangular core. The lower experimentally demonstrated power density is attributed to core attribute deviations and to rectification losses. Experiments with a 1000-turn, 1:7 funnelling ratio ferrite core device, shown in the inset photo of Fig. 7, yielded 240 mV and 360 mV open circuit voltage amplitude from 20 A and 30 A emulated distributed current respectively. These correspond to 20 µW/g (46 µW/cm^3) and 36 µW/g (106 µW/cm^3) respectively (green squares in Fig. 6). The 20 A and 30 A distributed current values used correspond to the total current in a single flange of the structure, without and with the skin effect at 300 Hz. Precise fitting of simulations to the experimental conditions was avoided to maintain clarity in the simulation study.

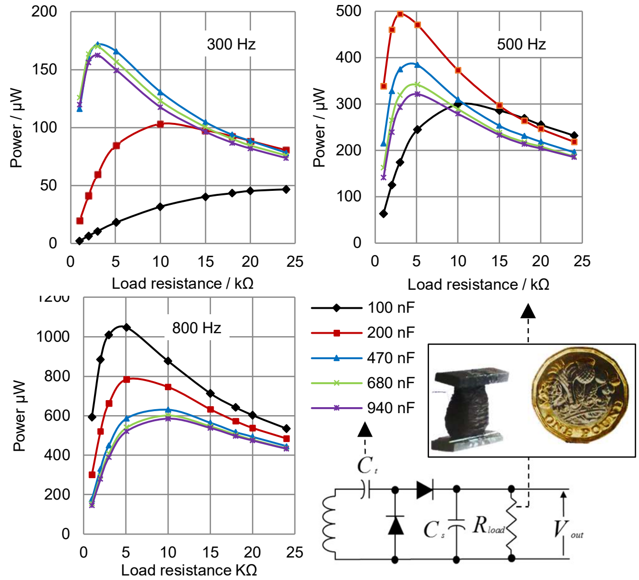

Fig. 7: Measurements from the Schottky voltage doubler circuit (bottom right) demonstrating harvesting power in the 0.1 – 1 mW range, reactance elimination by tuning C_t and load matching for three different frequencies. A photograph of the 1:7 funneling device is also shown.

V. CONCLUSIONS

The possibility of inductive energy harvesting from the magnetic field of current-carrying structural beams was evaluated in this paper. The current distribution plays an important role and the skin effect can result in current accumulation at edges even at low frequencies (10 Hz – 1000 kHz). This can increase the output power if a beneficial installation location is selectable. For aircraft structural beams, simulations show a ×4 and a ×5 power benefit at edges, at 300 Hz and 1 kHz respectively, in comparison to the beam centre. The employment of a ferrite core is shown to provide a power enhancement of ×36, or ×4 in power density (power per unit mass of the core-coil system), and ×6.5 in power density per volume.

The power density can be further increased by adopting funnel-like core structures to guide more flux through smaller coil frames, reducing coil resistance as well as core mass. A power density improvement of over ×49 is demonstrated by simulation from this method, in comparison to a coreless coil.

Experimental results using a rectangular core prototype demonstrate a rectified power density of 13.7 µW/g delivered to a storage capacitor, from a distributed 20 A current at 300 Hz, and 84.4 µW/g at 800 Hz. An impedance matching study shows that the maximum power transfer can be achieved by tuning the input capacitor of a voltage doubler circuit to eliminate the coil reactance, and match the load resistance to the resistance of the coil, in line with the theoretically expected $Z_{load} = Z_{out}^*$ maximum power transfer point condition, where Z_{load} and Z_{out}^* are the load impedance and the conjugate of the transducer output impedance.

Experimental results from a 1:7 flux funnelling device demonstrate 20 µW/g (46 µW/cm^3) and 36 µW/g (106 µW/cm^3) respectively from a distributed 20 A and 30 A current respectively at 300 Hz. For comparison, the bow-tie shaped device results reported in [9] can be extrapolated to the simulated magnetic flux density and frequency of this work (spatial average 3.5 µT RMS, 300 Hz), giving 0.4 mW/cm^3. The flux guiding device in [8] provides around 16 mW/cm^3 from a 200 A RMS, 60 Hz current power line, while [7] reports 0.6 mW/cm^3 from 0.9 A RMS, 620 Hz and [6] reports 10 µW/cm^3 from a household power line. Nevertheless, a direct figure-of-merit comparison among implementations is avoided due to substantial field source differences, especially given the varying distributed current in the structures studied in this work.

The employment of optimized funnel shaped geometries and tunable maximum power point tracking circuits is expected to enable inductive energy harvesting devices functional in various magnetic field sources, including both cable and structural current carriers. It is particularly suitable for powering sensors on aircraft or other vehicles, where structural beams are used as the return current path for variable frequency electrical power. In combination with other approaches such as flux guiding [8], it may also relax the installation location requirements, by extending the vicinity of operation.

ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785495 and Project AMPWISE. This document reflects only the author's view and the Commission is not responsible for any use that may be made of the information it contains.

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