Power Electronic Systems
Laboratory

Proceedings of the International Power Electronics Conference - ECCE Asia (IPEC 2014), Hiroshima, Japan, May 18-21, 2014

Optimizing Repulsive Lorentz Forces for a Levitating Induction Cooker

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Optimizing Repulsive Lorentz Forces for a Levitating Induction Cooker

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***Abstract*—In this paper we study a novel way of induction cooking. Traditionally, an alternating magnetic field is used to induce currents in a ferromagnetic pan to heat foods. We use non-ferromagnetic materials and optimize the design for high repulsive forces in order to levitate the pan while simultaneously heating it and its contents. Our approach is simulation-based to study the influence of different parameters and to perform multidimensional analyses for high force versus power or loss goals. Finally, an experimental prototype has been realized and successfully operated.**

***Index Terms*—Magnetic levitation, modeling, eddy currents, induction motors, induction cooking, home appliances, education**

I. Motivation

The proliferation of induction cookers is constantly growing. Compared to traditional electrical stoves, quick reaction time and – depending on the source – high energy efficiency speak for them [1]. In a typical induction cooker, a flat induction coil creates an alternating magnetic field. The field induces a current flow in the conducting pan on top of the coil [2]. This leads to losses in the pan caused by its electrical resistance, heating up the pan and its contents. The currents in the two coupled coils (excitation coil and pan) also have a force effect. In this publication, we investigate if these forces can be used to levitate the pan. Further, we study design variants targeting stable levitation and concentration of the losses in the pan and keep them away from the excitation – or bearing – coil(s). A design variant is shown in Figure 1.

While newer developments [3] override this restriction, in conventional induction stoves the base of the pan must typically contain ferromagnetic material. Such materials conduct the magnetic field well and concentrate the magnetic flux. This primarily leads to a lower skin depth (higher resistance) as well as to a reduction of the flux path and consequently to an attracting force owing to the reduced reluctance. The current flow in the base of the pan is opposed to the one in the excitation coil, why a repulsive force is created (Lorentz force). The minimization of this force is often the goal of optimizations in applications like metal production [4]. In our investigation, we follow a completely different approach: that of maximizing Lorentz forces in order to allow the pan to levitate so that an observer may witness an air gap between the excitation/cooktop surface and the pan.

Generally, high excitation currents lead to high repulsive forces. But there are limits on the excitation current because the removal of ohmic losses in the excitation coil becomes more and more challenging. Thus one criterion for optimization is to maximize the quotient of losses in the pan versus losses in the excitation coil. A further criterion is the maximization of the bearing force at a certain loss level.

To simplify the construction, solely repulsive magnetic fields shall be used. Additionally, no parts shall be added to the pan (permanent magnets, coils, back iron). For this reason, active, top or radially acting magnetic bearing designs will not be considered.

Figure 1: Design variant of a levitated induction cooker.

II. Previous Works

The principle involved in using eddy currents for heating and levitation is not new. Previous works include applications on contactlessly melt metals [5] and many educational exhibits. We use an eddy current bearing in one of our lectures to demonstrate a very simple magnetic bearing where the levitated object gets very hot quickly. In science and technology museums one can often find an exhibit with a levitating aluminum ring on top of a coil connected to the mains [6, 7].

What is new about our device is that we want to apply said principle for cooking such as a demonstration of induction or as a show effect.

III. Analysis

The shape of the pan has a great influence on the force development. The strongest vertical forces (high axial stiffness) act on surfaces orthogonal to the coil axis, but these surfaces cause no radial stiffness; therefore, a pan consisting solely of such surfaces (e.g. a sheet) would simply slip out and fall down. On the other hand, a spherically shaped pan offers a positive radial stiffness but, despite the tendency to right itself, it has a zero tilting stiffness. A flat bowl/plate shaped pan offers a positive axial, radial and tilting stiffness and is thus researched.

For an efficient excitation, the excitation coil is operated in a (series) resonant circuit. As the pan moves, the inductance changes and hence, the resonant frequency. Experiments have shown that without any extra means of damping, the levitated pan would oscillate and eventually touch the coil surface or even fall out. We adaptively control the excitation frequency by tracking the coil current.

Assuming that the major part of the flux in the excitation coil induces a current in the pan and that the pan is thick enough to shield the field, an increase of the coil radius leads to an increase of the current in the pan and – at a constant air gap field strength – to a proportional increase of the Lorentz force acting on the pan.

At a fixed geometry and air gap, the coupling between excitation and pan is constant. A higher excitation current then leads to a proportionally higher magnetic air gap field and current in the pan. The Lorentz force acting on the pan is proportional to the current in the pan and air gap flux density which is again proportional to the air gap field. Therefore this force should increase with the excitation current squared.

IV. Simulation

To verify the feasibility of the concept and to optimize the design, a simulative approach has been chosen. Due to the rotational symmetry, all simulations were 2D FEM-based in a cylindrical coordinate system in the eddy current domain. All dimensions were parameterized in order to allow variation and tuning runs, since with today's computer power, multidimensional searches could be performed within only hours (for example frequency versus coil diameter and pan thickness).

Figure 2 shows the simulation model used for a simple cylindrical pan. The mesh in the levitated object (Pan) was manually adjusted to include multiple elements in the material thickness.

The coil below was excited with a fixed amplitude AC current. This constant current excitation was used because in the experiment the number of turns and maximum amplifier current are fixed while independent of the inductance, the resonant tank can always be tuned to push the voltage amplitude high enough to drive that current.

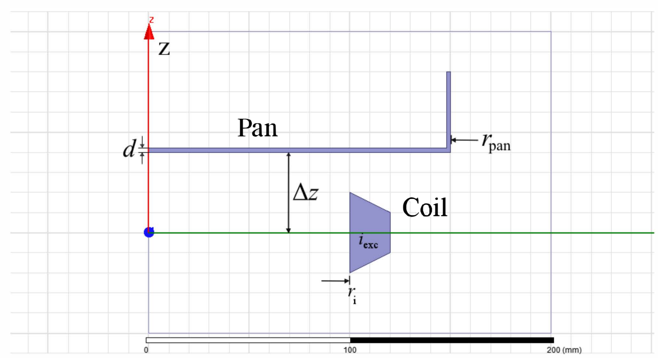

Figure 2: Model of a magnetically levitated induction cooker. The vertical (z) axis shows the rotational symmetry. The excitation coil is stranded and supplied with a fixed amplitude AC current.

As expected, the following proportionalities of the repelling force F were confirmed:

F	$\propto$	r_i	Inner coil radius r_i
	$\propto$	i_exc^2	Ampere turns i_exc of excitation
	$\propto$	$\cos(\alpha)$	Pan wall angle α
	$\propto$	$1/\Delta z$	Vertical distance Δz between excitation coil center and pan

Figure 3 shows that the repelling force acting on the pan rises proportionally to the excitation coil radius. If the pan is

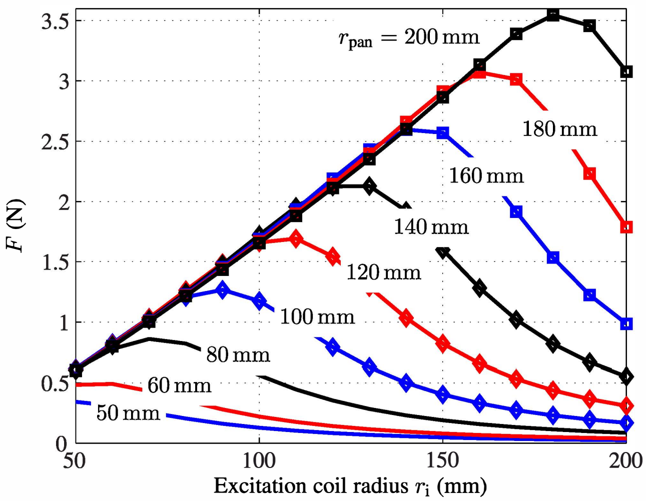

Figure 3: Simulated force F as a function of the excitation coil radius r_i at different pan radii r_{pan} (flat aluminum pan, $i_{exc} = 1000\,A \cdot turns$, $h_{pan} = 33\,mm$, radial excitation coil thickness: $20\,mm$).

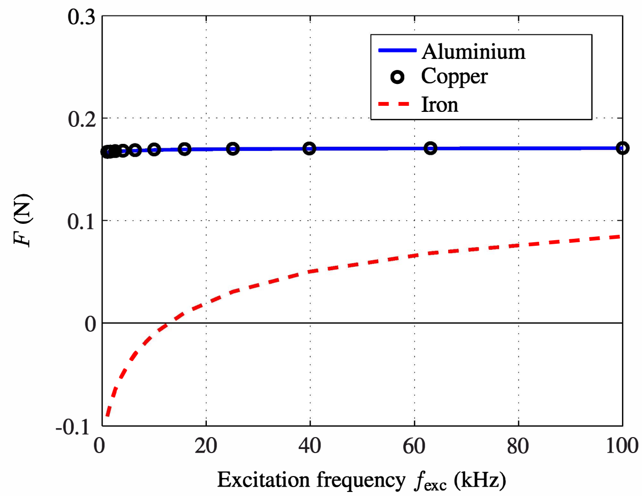

Figure 4: Force F as a function of excitation frequency f_{exc} at different pan materials ($i_{exc} = 500\,A \cdot turns$, $h_{pan} = 40\,mm$, $r_i = 50\,mm$). Aluminum and copper show no significant difference, while iron generally generates lower repulsive forces, yet (at low frequencies) produces attracting forces.

smaller than the excitation coil, the force starts to decrease again, so matched pan and coil sizes are important.

Good conducting materials (Al, Cu) lead to repulsive forces with little dependency on f_{exc} (Figure 4). The forces are similar in both materials, but aluminum being about three times lighter than copper, the air gap will be wider at the same current. Iron (Fe-1010) reveals a strong dependency on f_{exc} in the studied frequency range, even showing attracting forces when remanence dominates at frequencies below 12 kHz. Due to the high resistivity of iron, the force versus heating power quotient is also low.

In Figure 5, the dependence of the force on the excitation frequency f_{exc} and the pan thickness d is shown. The highest repelling force is generated with a pan thickness of about 4/7 of the corresponding skin depth. This finding has been tested against different materials (Aluminum, Copper and Magnesium) and frequencies ($f_{exc} = 1\,kHz...100\,kHz$). If the pan is thinner, the force decreases rapidly. If the pan is thicker, the decrease is less. At a constant excitation current, however, the heating power rises fast, hence, depending on the application – heating power versus levitation – an optimum can be found.

Studies on the influence of the excitation current i_{exc} and levitation height Δz at two different coil radii $r_i = \{50\,mm, 100\,mm\}$ were performed (Figure 6 and Figure 7). While in both designs, the force increases with the current squared, the smaller coil only allows for levitated loads in a low range, even at higher currents or small gaps.

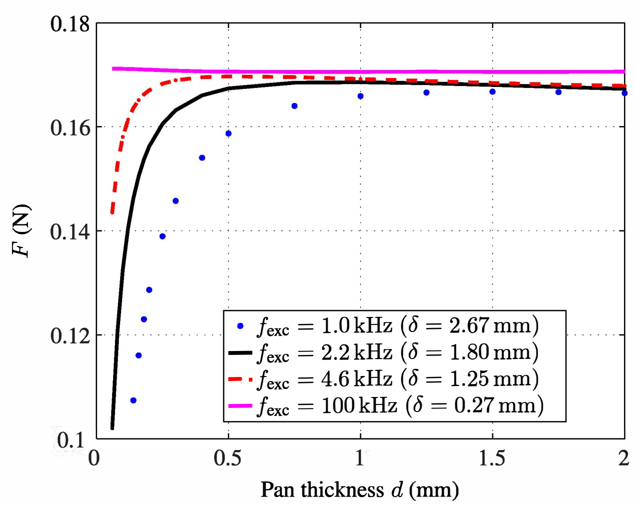

Figure 5: Force F as a function of the pan thickness d at different excitation frequencies f_{exc} ($i_{exc} = 500\,A \cdot turns$, $h_{pan} = 40\,mm$, $r_i = 50\,mm$, aluminum pan). At low frequencies ($< 30\,kHz$) a force maximum can be found near $d = 4/7 \cdot \delta$ with the skin depth δ.

The decreasing force with increasing gap size Δz (Figure 8) can be approximated by a hyperbolic curve $1/h_{pan}$. The decrease is due to the smaller coupling which eventually leads to less ohmic losses in the levitated pan than in the excitation coil at high distances (Figure 9). In the range studied, the loss distribution is solely a function of the geometry, independent of the electrical excitation.

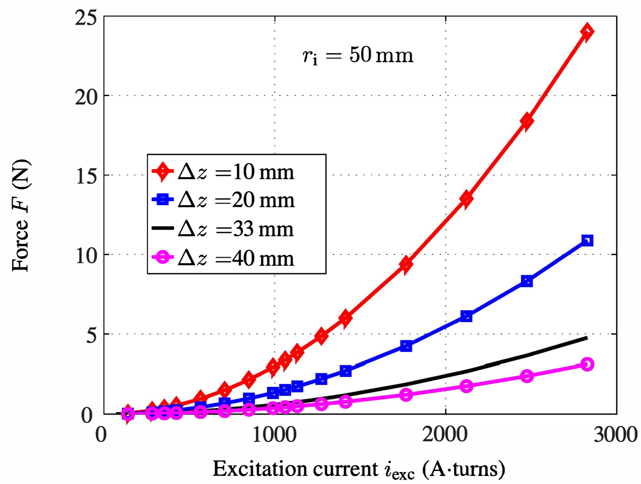

Figure 6: Simulated force F as a function of the excitation current i_{exc} at different gaps Δz ($r_i = 50\,\mathrm{mm}$).

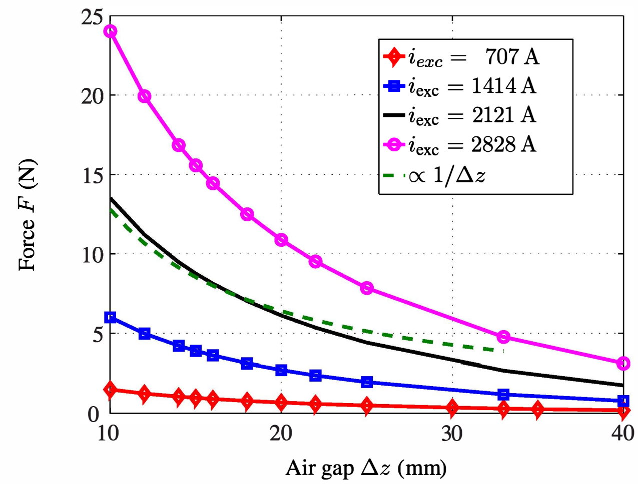

Figure 8: Simulated force F as a function of the air gap Δz at different excitation currents i_{exc} ($r_i = 50\,\mathrm{mm}$, $f_{exc} = 10\,\mathrm{kHz}$).

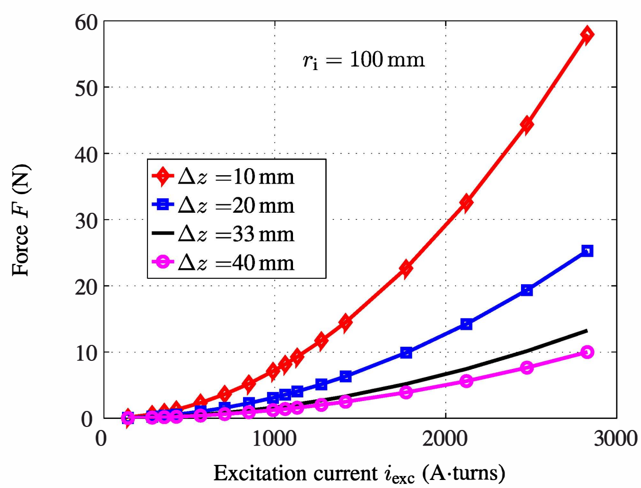

Figure 7: Simulated force F as a function of the excitation current i_{exc} at different gaps Δz ($r_i = 100\,\mathrm{mm}$).

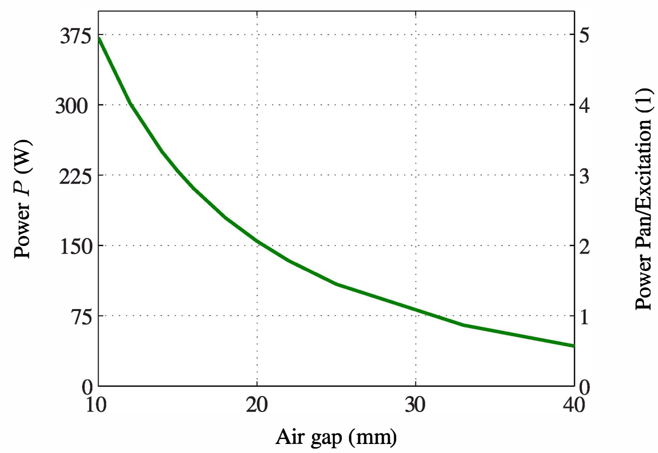

Figure 9: Simulated ohmic losses in the pan at $i_{exc} = 1000\,\mathrm{A \cdot turns}$. The loss ratio pan/excitation goes below one at wider air gaps h_{pan} ($r_i = 50\,\mathrm{mm}$, $f_{exc} = 10\,\mathrm{kHz}$).

To give an example, levitating a load of $m = 3\,\mathrm{kg}$ (Typical caquelon pan and fondue contents for a party of four), using a coil with an inner radius of $r_i = 100\,\mathrm{mm}$, at a level of $\Delta z = 10\,\mathrm{mm}$, needs a current of $i_{exc} = 2\,\mathrm{kA \cdot turns}$. This current produces ohmic losses on the pan of $P = 1.5\,\mathrm{kW}$ which is sufficient for cooking applications.

V. Experiment

A small-scale prototype was built and successfully operated. Levitation and heating have been demonstrated but at a much smaller scale than conventional induction cookers. Table I shows some key data of the first prototype. In Figure 10, the experimental setup is shown: on the left side, the trapezoidal shaped coil with an aluminium test pan on top. On the right side are series resonance capacitors, voltage and current probes. The setup was powered from a commercial square wave voltage source ($48\,\mathrm{V}$, $10\,\mathrm{Arms}$, DC...$150\,\mathrm{kHz}$, PWM).

Figure 11 shows the electrical characteristics of the excitation coil modelled as a series connected R-L circuit. The bearing coil being made of liz wire, there is little change in the series resistance R_s up to an excitation frequency $f_{exc} = 50\,\mathrm{kHz}$). Starting at about $f_{exc} = 1\,\mathrm{kHz}$, the magnetic field of the excitation coil is completely shielded by the pan making the inductance and resistance stay constant relative to the unloaded coil. Since the quality factor of the coil

$$Q_L = \frac{2\pi \cdot f_{exc} \cdot L_s}{R_s}$$

is very high (at $f_{exc} = 18\,\mathrm{kHz}$: $Q_L = 350$ without load,

$Q_{\mathrm{L}} = 150$ with a plate and $Q_{\mathrm{L}} = 90$ with a pan at $\Delta z = 33\,\mathrm{mm}$), owing to the low damping of the large air gap, a high voltage gain in the resonant circuit results, shown in Figure 12.

Table I: Key parameters of the experimental setup

Parameter	Value
Configuration	series resonance
Coil radius	$r_{\mathrm{i}} = 50\,\mathrm{mm}$
Number of turns	$n = 99$
Unloaded coil inductance	$L_0 = 1.245\,\mathrm{mH}$
Operating frequency	$f_{\mathrm{exc}} = 16.7\,\mathrm{kHz}$

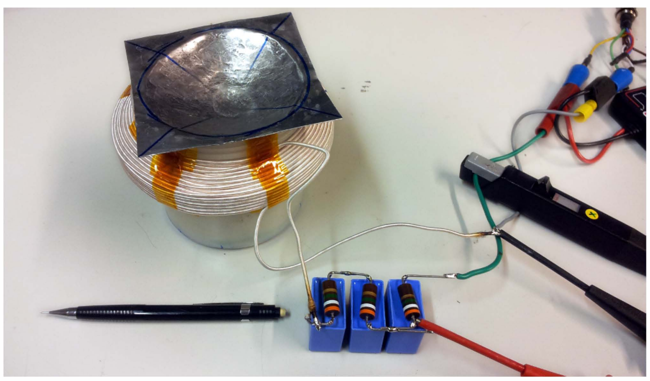

Figure 10: Prototype setup of a magnetically levitated induction cooker.

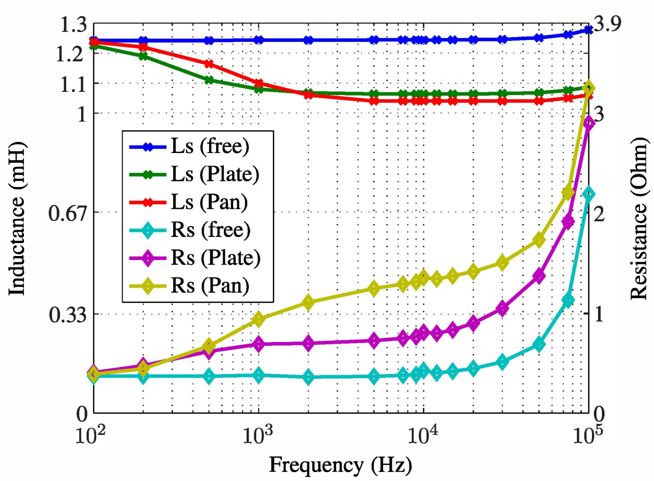

Figure 11: Series inductance L_{s} and resistance R_{s} of the coil as a function of the excitation frequency, operating in free space, loaded with a flat pan "Plate" and round pan ($21\,\mathrm{mm}$ deep, $92\,\mathrm{mm}$ radius of the depression).

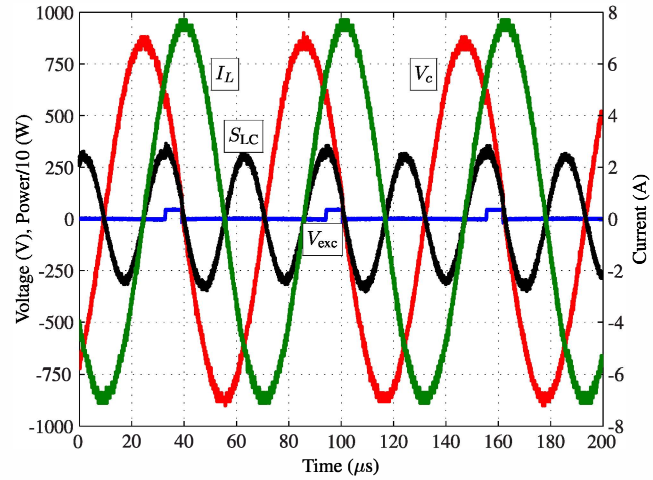

Figure 12: Measured voltage, apparent power and currents in the setup. Due to the big air gap, the quality factor of the resonant circuit is high, resulting in a high voltage V_c.

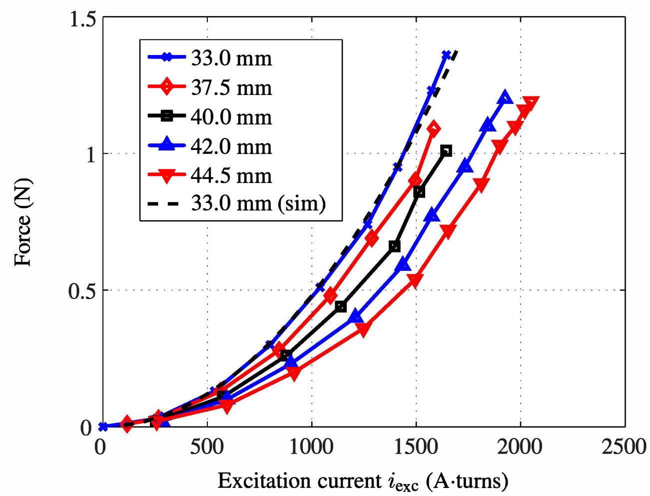

Figure 13: Force F as a function of the excitation current i_{exc} normalized to one turn at different gaps (Δz) comparing measured and simulated values.

The simulated forces in Figure 6 predict the measured values very good (Figure 13, the prototype has a lower limitation on Δz of 33mm).

VI. Discussion

To achieve a big air gap (a high levitation level), high excitation currents are needed ($F \propto i_{\mathrm{exc}}^2/\Delta z$ for gaps $\Delta z \ll$ diameter), which inherently lead to an elevated heating power. If this power is not needed the current has to be reduced and the gap will become smaller with the levitation effect being less apparent.

High excitation currents also lead to high losses in the excitation coil that have to be dealt with. While, in a conventional induction cooker, the excess heat from the excitation coil can be dumped into the pan to limit the coil's temperature to the pan's, this cannot easily be done here because of the weak thermal coupling between pan and excitation coil during levitation. We presume that an active (fan based) cooling of the excitation coil can hardly be avoided.

The repulsive force between excitation coil and prototype pan is quite small for cooking applications: as a result, heavier or bigger pans cannot be levitated without increasing excitation current and heating power to very high levels. Simulations of a bigger model were performed (Figure 7, $r_\mathrm{i} = 100\,\mathrm{mm}$). At bigger radii and excitation currents or smaller air gaps, significantly higher forces can be reached, but there are at least two downsides: First, the force only increases linearly with the radius, while the weight of the pan generally scales by volume, radius at the power of three. Second, simple air cooling of the excitation coil can only be performed at the coil surface which scales with the radius squared, so cooling of bigger coils or higher currents will become challenging.

The simple construction has the further disadvantage of low stiffness compared to actively controlled, PM-based or attracting magnetic bearings, which could be disadvantageous in relation to external disturbance forces (stirring, adding or removing material from the pan).

VII. Conclusions and Outlook

It has been shown that levitating a pan on an induction cooker is not only feasible, but can also be realized, be it as a small prototype or a typically sized pan including contents. The heating power is coupled to the repulsive force and is generally quite high. To increase the force-to-power quotient, the application of permanent magnet or reluctance based passive and active magnetic bearings should be studied.

Currently, the design is rotationally symmetric. Similar to an induction motor, further coils could be added to create a rotating magnetic field in order to spin the levitated pan. The lifting and driving fields could further be superimposed on the control circuit to allow for a simpler construction with fewer coils.

By using position sensors or applying one of the several published approaches for sensor-less control, an active control circuit could be realized to enhance the stiffness of the bearing including axial, tilting and radial movement. While the first do not need any additional coils, control of the later axes asks for independent control by e.g. the coils of the drive.

The current design has the advantage of boosting the heating power the closer the pan gets to the excitation coil. If there is less material in the pan (for example due to evaporation, boiling or removal), the gap is widened: this results in a lower heating power proving a passively safe behavior. Given that power is not reduced to zero with an empty pan, however, additional means of supervision are necessary, which may be implemented using a contactless IR-detector as proposed in [2].

As it is, state of the art levitating induction cookers open up new and exciting possibilities in Fondue event catering or culinary experiences which will not fail to amaze your guests.

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