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C. Zingerli,
T. Nussbaumer,
J. W. Kolar

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Optimizing Repulsive Lorentz Forces for a Levitating Induction Cooker

Claudius M. Zingerli^{*a)} Non-member, Thomas Nussbaumer^{**} Non-member
Johann W. Kolar^{*} Non-member

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In this paper, we present 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 nonferromagnetic materials and optimize the design for high repulsive forces in order to levitate the pan while simultaneously heating it and its contents. We use a simulation-based approach to study the influence of different parameters and to perform multidimensional analyses for the high force versus the power or loss goals. Finally, an experimental prototype is realized and successfully operated.

Keywords: magnetic levitation, modeling, eddy currents, induction motors, induction cooking, home appliances

1. 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 Fig. 1.

While newer developments⁽³⁾⁽⁴⁾ 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⁽⁵⁾. 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



Fig. 1. Design variant of a levitated induction cooker

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 the losses in the pan versus the 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.

2. Previous Works

The principle involved in using eddy currents for heating and levitation is not new. Previous works include applications on contactlessly melt metals⁽⁶⁾ 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⁽⁷⁾⁽⁸⁾.

What is new about our device is that we want to apply said

a) Correspondence to: Claudius M. Zingerli. E-mail: zingerli@lem.ee.ethz.ch

* ETH Zürich, Power Electronic Systems Laboratory
Physikstrasse 3, 8092 Zürich, Switzerland

** Levitronix GmbH
Technoparkstrasse 1, 8005 Zürich, Switzerland

principle for cooking such as a demonstration of induction or as a show effect.

3. 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.

4. 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 trapezoidal shape of the coil allows for a high winding density and does not require additional supports.

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.

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

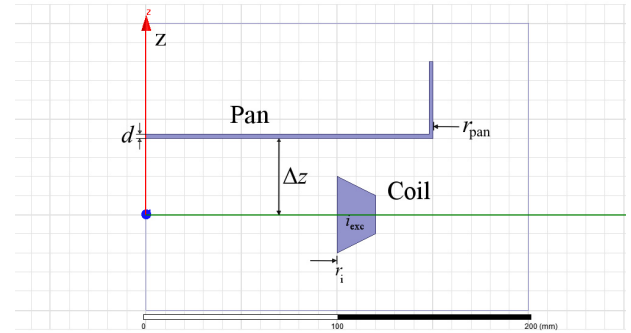


Fig. 2. Model of a magnetically levitated induction cooker. The vertical (z) axis shows the rotational symmetry. The excitation coil is stranded and supplied with a fixed amplitude AC current

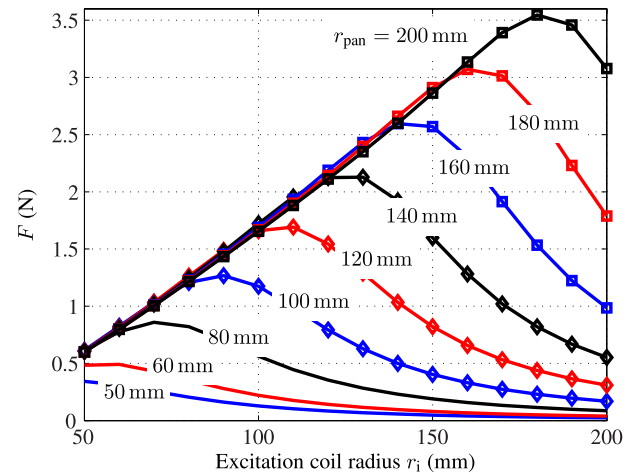


Fig. 3. Simulated force F as a function of the excitation coil radius r_i at different pan radii r_{pan} (flat aluminum pan, $i_{exc} = 1000 \text{ A} \cdot \text{turns}$, $\Delta z = 33 \text{ mm}$, radial excitation coil thickness: 20 mm)

$F \propto r_i$	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

These proportionalities are not necessarily universal, but apply to the dimensions and currents studied and shown in the figures of this paper.

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

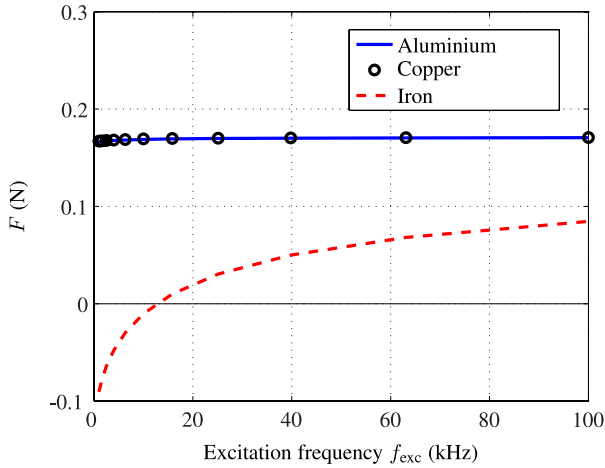


Fig. 4. Force F as a function of excitation frequency f_{exc} at different pan materials ($i_{exc} = 500 \text{ A} \cdot \text{turns}$, $\Delta z = 40 \text{ mm}$, $r_1 = 50 \text{ mm}$). Aluminum and copper show no significant difference, while iron generally generates lower repulsive forces, yet (at low frequencies) produces attracting forces

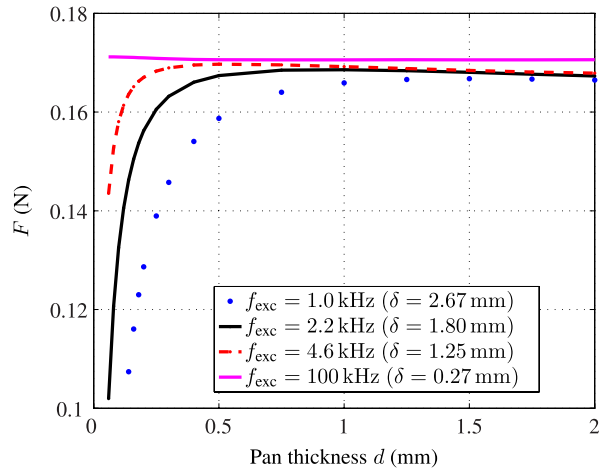


Fig. 5. Force F as a function of the pan thickness d at different excitation frequencies f_{exc} ($i_{exc} = 500 \text{ A} \cdot \text{turns}$, $\Delta z = 40 \text{ mm}$, $r_1 = 50 \text{ mm}$, aluminum pan). At low frequencies ($< 30 \text{ kHz}$) a force maximum can be found near $d = 4/7 \cdot \delta$ with the skin depth δ

of the corresponding skin depth. This finding has been tested against different materials (Aluminum, Copper and Magnesium) and frequencies ($f_{exc} = 1 \text{ kHz} \dots 100 \text{ kHz}$). 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 $r_1 = \{50 \text{ mm}, 100 \text{ mm}\}$ were performed (Figs. 6 and 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.

The decreasing force with increasing gap size Δz (Fig. 8) can be approximated by a hyperbolic curve $1/\Delta z$. The decrease is due to the smaller coupling which eventually leads to less ohmic losses in the levitated pan than in the excitation

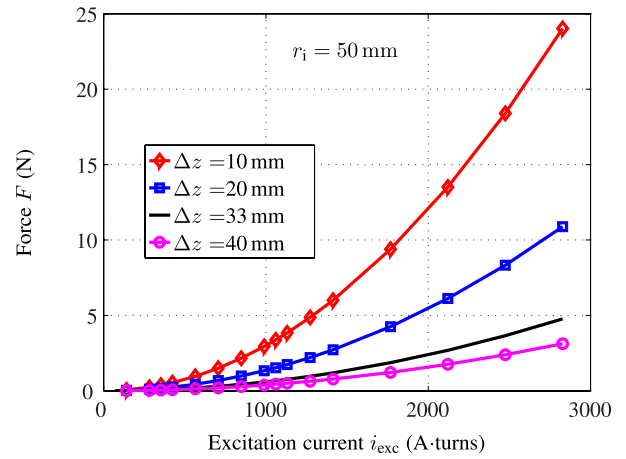


Fig. 6. Simulated force F as a function of the excitation current i_{exc} at different gaps Δz ($r_1 = 50 \text{ mm}$)

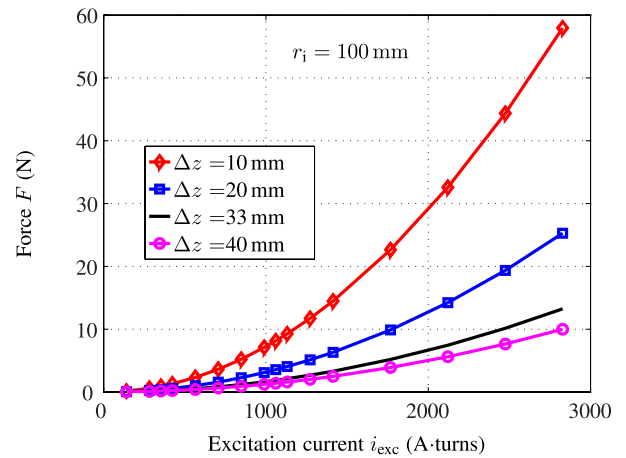


Fig. 7. Simulated force F as a function of the excitation current i_{exc} at different gaps Δz ($r_1 = 100 \text{ mm}$)

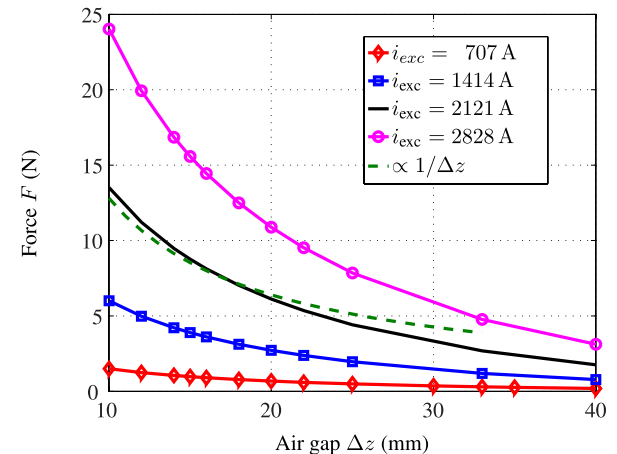


Fig. 8. Simulated force F as a function of the air gap Δz at different excitation currents i_{exc} ($r_1 = 50 \text{ mm}$, $f_{exc} = 10 \text{ kHz}$)

coil at high distances (Fig. 9). In the range studied, the loss distribution is solely a function of the geometry, independent of the electrical excitation.

To give an example, levitating a load of $m = 3 \text{ kg}$ (Typical caquelon pan and fondue contents for a party of four), using a coil with an inner radius of $r_1 = 100 \text{ mm}$, at a level of

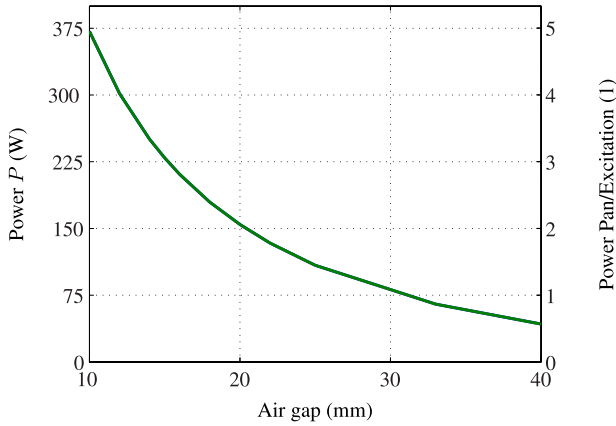


Fig. 9. Simulated ohmic losses in the pan at $i_{exc} = 1000 \text{ A} \cdot \text{T}$. The loss ratio pan/excitation goes below one at wider air gaps Δ_z ($r_1 = 50 \text{ mm}$, $f_{exc} = 10 \text{ kHz}$)

$\Delta z = 10 \text{ mm}$, needs a current of $i_{exc} = 2 \text{ kA} \cdot \text{turns}$. This current produces ohmic losses on the pan of $P = 1.5 \text{ kW}$ which is assumed sufficient for cooking applications.

5. Experiment

First, small-scale prototype was built and successfully operated. Levitation and heating have been demonstrated but at a much smaller scale than conventional induction cookers. In Fig. 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 V, 10 Arms, DC...150 kHz, PWM). Table 1 shows some key data of the first prototype.

Figure 11 shows the electrical characteristics of the excitation coil modelled as a series connected R-L circuit. The bearing coil being made of litz wire, there is little change in the series resistance R_s up to an excitation frequency $f_{exc} = 50 \text{ kHz}$. Starting at about $f_{exc} = 1 \text{ kHz}$, 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 $f_{exc} = 18 \text{ kHz}$: $Q_L = 350$ without load, $Q_L = 150$ with a plate and $Q_L = 90$ with a pan at $\Delta z = 33 \text{ mm}$), owing to the low damping of the large air gap, a high voltage gain in the resonant circuit results, shown in Fig. 12. The inductance is further a function of the position of the pan, so for optimal results a resonance tracking algorithm is needed on the control system (Depending on the excitation source, this could be a simple current or voltage zero-crossing detection or a maximum power point tracker like for example a perturb and observe-algorithm controlling the excitation frequency based on coil current, which could be easier to implement on digital systems).

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

While the setup in Fig. 10 allowed for the demonstration of

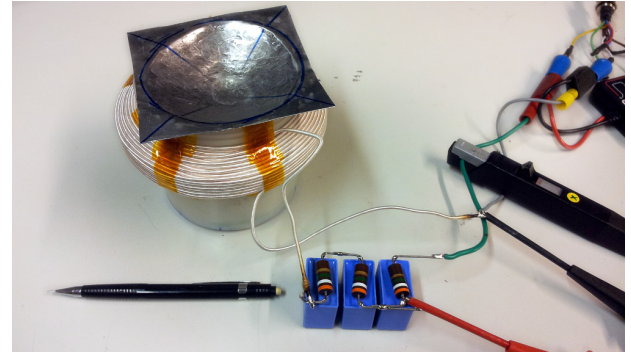


Fig. 10. Prototype setup of a magnetically levitated induction cooker

Table 1. Key parameters of the experimental setup

Parameter	Value
Configuration	series resonance
Coil radius	$r_1 = 50 \text{ mm}$
Number of turns	$n = 99$
Unloaded coil inductance	$L_0 = 1.245 \text{ mH}$
Operating frequency	$f_{exc} = 16.7 \text{ kHz}$
Series capacitor value	$C_s = 73 \text{ nF}$

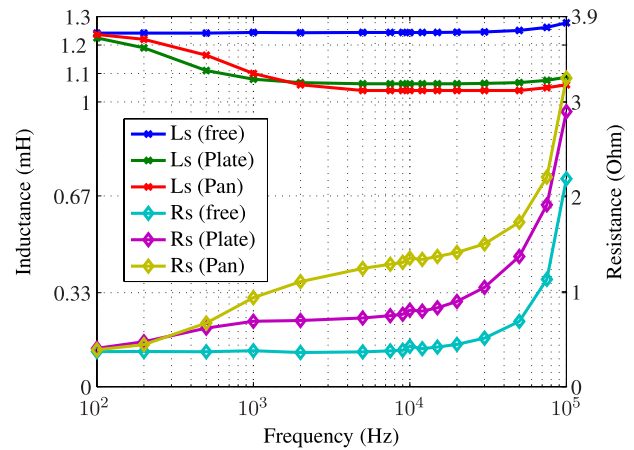


Fig. 11. Series inductance L_s and resistance R_s of the coil as a function of the excitation frequency, operating in free space, loaded with a flat pan "Plate" and round pan (21 mm deep, 92 mm radius of the depression)

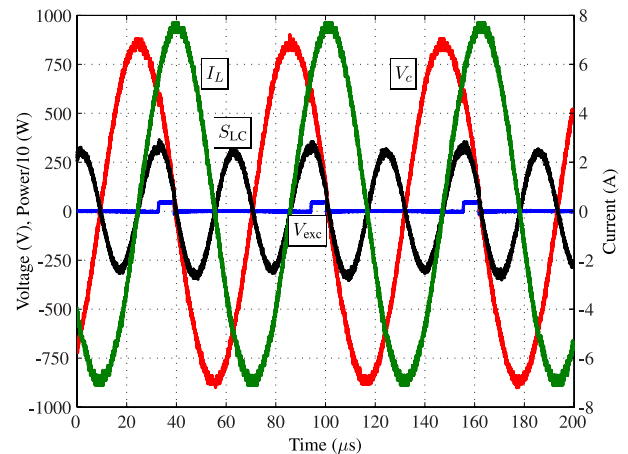


Fig. 12. Measured voltage, apparent power and currents in the setup. Due to the big air gap, the quality factor of the resonant circuit is high, resulting in a high voltage V_c

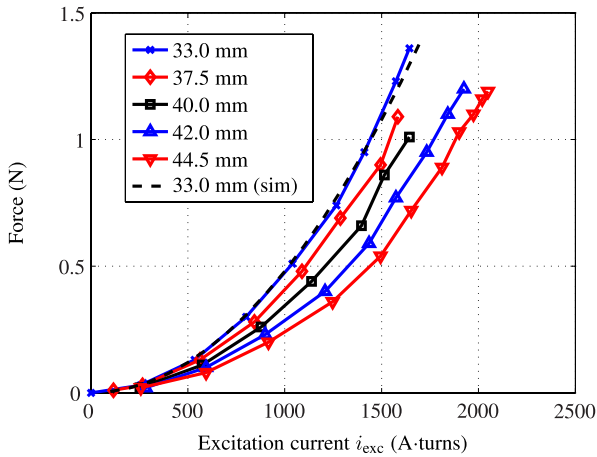


Fig. 13. Force F as a function of the excitation current i_{exc} normalized to one turn at different gaps (Δz) comparing measured and simulated values (sim)



(a) Bottom view



(b) Top view

Fig. 14. Improved prototype for cooking demonstrations ($r_i = 200$ mm, $\Delta z \approx 30$ mm). The edge of the aluminium pan is M-shaped for high radial and tilting stiffness

a stable axial bearing, to improve radial force and returning tilting torque for levitated cooking, the usage of a pan with an M-shaped edge is recommended, as shown in Fig. 14.

6. Discussion

To achieve a big air gap (a high levitation level), high excitation currents are needed ($F \propto i_{exc}^2 / \Delta z$ 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 (Fig. 7, $r_i = 100$ 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).

7. 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).

While our main application is cooking and educational exhibits, the contactless nature of the system could just as well be used in very sensitive applications where for example vibration, contamination or temperatures must be separated between heater and good.

Acknowledgment

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Claudius M. Zingerli (Non-member) was born in Thal, Switzerland in 1984. He received the Dipl.-Ing. degree (M.Sc.) in electrical engineering from the Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland, in 2009. During his studies, he did research on sensing and advanced control of magnetic bearings for high-speed electrical drive systems. He is currently working toward the Ph.D. degree at the Power Electronic Systems Laboratory (PES), Swiss Federal Institute of Technology (ETH) Zurich in the area of bearingless machines and drives. His main research interests include power electronics, converters, digital control and sensor systems.



Thomas Nussbaumer (Non-member) was born in Vienna, Austria, in 1975. He received the M.Sc. degree (Hons.) in electrical engineering from the University of Technology Vienna, Vienna, in 2001, and the Ph.D. degree from the Power Electronic Systems (PES) Laboratory, Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland, in 2004. From 2001 to 2006, he was with the PES, where he was involved in research on modeling, design, and control of three-phase rectifiers, power factor correction techniques,



and electromagnetic compatibility. Since 2006, he has been with Levitronix GmbH, Zurich, where he is currently involved in research on bearingless motors, magnetic levitation, and permanent-magnet motor drives for the semiconductor and biotechnology industry. His current research is focused on compact and high-performance mechatronic systems including novel power electronics topologies, control techniques, drive systems, sensor technologies, electromagnetic interference, and thermal aspects.

Johann W. Kolar (Non-member) received his M.Sc. and Ph.D. degrees (summa cum laude) from the University of Technology Vienna in 1997 and 1998, respectively. Since 1982 he has been working as an international consultant in the fields of power electronics, industrial electronics and high performance drives. He is currently a Full Professor and the Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich. He has proposed numerous novel PWM converter topologies,



and modulation and control concepts, e.g., the Vienna Rectifier, the Swiss Rectifier, and the AC-AC Sparse Matrix Converter. Dr. Kolar has published over 550 scientific papers in international journals and conference proceedings and has filed more than 110 patents. He received 9 IEEE Transactions Prize Paper Awards and 8 IEEE Conference Prize Paper Awards. The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, on the realization of ultra-compact/efficient converter modules employing latest power semiconductor technology (SiC and GaN), Power Supplies on Chip, multi-domain/scale modeling/simulation and multi-objective optimization, and ultra-high speed and bearingless motors.