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Klevis Ylli · Yiannos Manoli

Energy Harvesting for Wearable Sensor Systems

Inductive Architectures for the Swing Excitation of the Leg

Springer

Klevis Ylli
Hahn-Schickard
Villingen-Schwenningen,
Baden-Württemberg, Germany

Yiannos Manoli
Department of Microsystems Engineering
University of Freiburg
Freiburg, Baden-Württemberg, Germany

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Preface

The term "Energy Harvesting" describes the generation of small amounts of electrical energy from the surrounding environment, be it kinetic energy, light or heat gradients. This technology offers the potential for the low-maintenance operation of wireless sensor systems without the need to charge or replace batteries. In order to power electronic systems on the human body, harvesting devices are being developed that use the body as an energy source. This book focuses on the human gait as a source of kinetic energy. The swing motion of the foot during walking provides the necessary excitation for flat inductive devices that can be integrated into the shoe sole. These devices are, in principle, comparatively simple to understand and fabricate. The main difficulty lies with the optimization of the geometrical parameters.

Several harvester architectures are investigated in this book, in order to find the magnet-coil arrangement that generates the largest power output. Before devices can be fabricated, the optimal geometrical parameters for the highly restricted space in the shoe sole need to be determined. A system model based on a differential equation of motion is developed that takes the relevant physical effects into account, i.e. the forces that act on the moving magnets and affect their motion. The steps taken to implement the required aspects of the system model in a numerical simulation environment are described in detail, and the model is subsequently used to calculate the motion of the magnets relative to the coils depending on the external excitation. The required simplifications as well as the drawbacks and limitations of the system model are described.

Based on the magnet motion, the induced voltage and the generated power output are determined. While the magnetic field distribution needs to be calculated for every setup separately, the system model is flexible and used across all architectures. The geometrical parameters of each architecture are variable, and an optimization algorithm is used to maximize the power output for each architecture.

The fabrication of harvester devices as closely as possible to the optimized design is the next step. The devices are characterized on a treadmill with two different test persons and at walking speeds of 4, 6, 8 and 10 km/h. The power output is determined using an ohmic load equal to the coil resistance. Of the four analyzed architectures, the highest achieved average power output is 10.32 mW. In terms of power density, this translates into 1.15 mW/cm^3 for an active volume of 8.96 cm^3. The maximum device dimensions including the housing remain the same throughout this work at 77 mm in length, 41.5 mm in width and 15.75 mm in height (resulting in a total volume of 50.33 cm^3).

The experimental results are used to revise and verify the system model. A new parameter optimization is performed for each architecture using the revised model. The second generation of fabricated devices (device volume remains 50cm^3) achieves a greatly improved average power output of up to 43 mW during walking (power density of 0.85 mW/cm^3).

Experiments are also carried out in industrial applications on a pneumatic piston and a pneumatic clutch-brake with power outputs reaching up to 15 mW. These results prove that this type of linear, non-resonant device can also be used in industrial applications where the excitation, while certainly not identical to human motion, shows a few similarities like non-resonant behavior and large amplitudes.

Lörrach, Germany Klevis Ylli
Freiburg, Germany Yiannos Manoli

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Nomenclature

Abbreviations

BLE	Bluetooth Low-Energy
BWS	Body-worn systems
CMS	Condition-monitoring system
DOE	Design of experiments
edf	Electrical damping force
EH	Energy harvester
FEM	Finite element method
GCS	Global coordinate system
GP	Geometrical parameters
HAC	Harvester architecture
INT1	Integrator 1 of the system model, etc.
IR	Infrared
LCS	Local coordinate system
LED	Light-emitting diode
MOGA-2	Multi-Objective Genetic Algorithm, used in parameter optimization
N35	Polarization strength of NdFeB permanent magnets
NdFeB	Neodymium iron boron (rare earth permanent magnet material)
O1	Data set from first optimization run. O2 Analogously
PCB	Printed circuit board
PV	Photovoltaic (cell)
RF	Radio-frequency
RMS	Root-mean-squared value
S1	Piston setup S1 in laboratory experiments. S2 and S3 analogously
WSN	Wireless sensor node

Symbols

A	Area enclosed by coil windings (m^2)
A_{ext}	External acceleration (e.g. from measurements of the foot motion) (m/s^2)
b_{mag}	Thickness of rectangular magnets (m)
B	Magnetic flux density (T)
B_{mean}	Mean flux density (e.g. for a given coil winding) (T)
B_x	X-component of magnetic flux density B (perpendicular to the direction of motion of the magnets in a cuboid setup) (T)
B_z	Z-component of magnetic flux density B (along the direction of motion of the magnets) (T)
c_v	Transition approximation coefficient of the friction model (s/m)
distInnen	Vector of the coil positions within the harvester housing. Used in the system model
d_{coil}	Thickness of cylindrical and rectangular coils (m)
d_{Cu}	Diameter of the copper wire used to wind the coils (m)
d_{iron}	Back flux guide thickness (“back iron”) (m)
d_{mag}	Wall thickness of ring magnets (m)
d_{Spacer}	Thickness of steel spacers (m)
f_c	Viscous friction coefficient (N/m/s)
F_{brk}	Breakaway friction force (N)
$F_{brk,S}$	Static breakaway friction force (N)
F_C	Coulomb friction force (N)
F_{el}	Electrical damping force (N)
F_R	Friction force (N)
F_S	Spring force (N)
F_T	Inertial force (N)
F_V	Viscous friction force (N)
g	Earth’s gravity (m/s^2)
h_{coil}	Length of the edge of the rectangular coil located along the direction of motion (m)
h_{core}	Size of the air gap in the middle of the coil (same direction as h_{coil}) (m)
h_{mag}	Magnet height (m)
H_c	Coercive field strength of magnets (A/m)
$k(x)$	Electro-magnetic coupling function (V/m/s)
k_i	Coefficient of restitution (hardstop model) (–)
l_{coil}	Length of the edge of the rectangular coil located perpendicular to the direction of motion (into the drawing plane of the FEM-simulation). Coil height in the case of cylindrical coils (m)
μ_k	Coefficient of kinetic friction (–)
μ_s	Coefficient of static friction (–)
μ_{mag}	Relative permeability (–)

m	Number of coil windings in the direction perpendicular to the winding area of a coil (–)
m_{mag}	Magnet stack mass (including steel flux guides where applicable) (kg)
n	Number of coil windings in the radial direction of a cylindrical coil, or in the direction of motion in the case of rectangular coils (–)
n_{coils}	Number of coils simulated/used in a harvester (–)
n_{mag}	Number of magnets simulated/used in a harvester (–)
N	Number of total windings of a coil (–)
φ	Magnetic flux (Wb)
P_{avg}	Average power output (mW)
P_N	Normalized power output (–)
ρ	Specific resistance of copper wire (Ω/m)
r_i	Radius of coil winding i (m)
r_{mag}	Inner magnet radius in the case of cylindrical magnets (m)
r_{mean}	Mean winding radius of a cylindrical coil (m)
R_{in}	Resistance of a coil (Ω)
R_l	Ohmic load resistance (Ω)
R_{mag}	Outer magnet radius in the case of cylindrical magnets (m)
R_{max}	Radius of the outermost (largest) winding of a cylindrical coil (m)
R_{min}	Radius of the innermost (smallest) winding of a cylindrical coil (m)
u_i	Logic signal number i in the Simulink environment (–)
U_{ind}	Induced voltage (V)
U_l	Voltage across the ohmic load (V)
v_{thr}	Threshold speed of the magnet in the friction model (m/s)
$\ddot{x}$	Magnet acceleration (m/s^2)
$\dot{x}$	Magnet speed (m/s)
x	Magnet position within housing (m)
x_{max}	Total motion space within the harvester housing (m)

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