

CITY UNIVERSITY OF HONG KONG  
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**A Novel Design in Harvesting Energy from  
Operating Machines by Converting Their  
Generated Waste Energies to Electricity**

從運行機器中提取廢棄能量而轉化成有用的電力之嶄新設計

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## Abstract

Wireless devices have been widely adopted in machine health monitoring because they can acquire data from machines that are operating and can be installed in hazardous environments. However, the major deficiency of wireless sensors is the need to replace batteries frequently. Moreover, it may be unsafe to change the batteries manually if the wireless devices are located in a hazardous environment. To overcome such deficiency, a novel alternative is to recharge the batteries by harvesting wasted energies generated from the ambient environment.

This study investigates the feasibility of implementation of an energy harvester to convert wasted energies generated from operating machines to electricity. In this research, three fundamental findings are observed. First, piezoelectric material, *QP20N*, is found to be a promising energy harvesting material to convert vibration to electricity. Second, the amount of power transfer can be optimized by matching the impedance of the piezoelectric material to that of the load. In addition, minimization of the internal impedance of the material can significantly increase its output power. Third, making the piezoelectric material vibrate at its resonance frequency will produce maximum electricity output. The most promising design of a piezoelectric-based energy harvester can be realized.

Based on the findings, a novel piezoelectric energy harvester was implemented using two designs: “frequency converter” and “inductor circuit”. In order to maximize the electricity output from the energy harvester, two criteria should be fulfilled. First, the harvester should be tuned by the “frequency converter” so that its resonance

frequency could be located within the dominant vibration frequency range of the operating machine. Second, the internal impedance of the piezoelectric material could be minimized by the “inductor circuit”. Maximum power transfer occurs when the impedance of the load matches that of the piezoelectric material. Experimental results show that the inductor circuit can increase the harvested power by at most 43% at the first mode of vibration of *QP20N*. Moreover, the power generated from *QP20N* by using a frequency converter can be 83 times much more than that from *QP20N* alone. The harvested energy can therefore partially supply electricity to power a low-power wireless device.

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## Nomenclatures

$A_c$	= active material of the energy harvesting transducer
$L_a$	= additional inductor
$\omega$	= angular frequency in chapter 4, natural frequency of the piezoelectric energy harvester in chapter 5
$I$	= area moment of inertia
$I_q$	= area moment of inertia of <i>QP20N</i>
$C$	= capacitance
$Q$	= charges
$A$	= cross sectional area
$A_p$	= cross sectional area of piezoelectric material
$[C]$	= damping matrix
$\omega_d$	= damped natural frequency
$c_1$	= damping of the frequency converter
$c_2$	= damping of the piezoelectric material
$\zeta$	= damping ratio
$R_p$	= dc resistance due to magnetic core loss of the additional inductor
$R_{dc}$	= dc resistance of the additional inductor
$\rho$	= density of the frequency converter
$\rho_q$	= density of <i>QP20N</i>
$y$	= displacement
$\eta$	= efficiency
$f_e$	= electrical resonance
$E_c$	= energy stored in the capacitor
$F$	= excitation force
$\beta$	= frequency ratio
$L$	= internal inductance in Chapter 4, length of frequency converter in Chapter 5
$L_0$	= inductance value of the additional inductor
$Z$	= internal impedance
$R$	= internal resistance
$L_q$	= length of <i>QP20N</i>

$R_L$	= load resistance
$[M]$	= mass matrix
$m_2$	= mass of the piezoelectric material
$M_b$	= mass of frequency converter
$\mu$	= mass ratio
$f_m$	= mechanical resonance
$E$	= modulus of elasticity
$\omega_1$	= natural frequency of the frequency converter
$\omega_2$	= natural frequency of the piezoelectric material on the frequency converter
$V$	= potential difference
$X_C$	= reactance of capacitance
$X_L$	= reactance of inductor
$m_1$	= resultant mass of the frequency converter and the mass at its free end
$C_0$	= self-capacitance
$[K]$	= stiffness matrix
$k_1$	= stiffness of the frequency converter
$k_2$	= stiffness of the piezoelectric material
$T_q$	= thickness of <i>QP20N</i>
$M$	= tip mass of the frequency converter
$\omega_n$	= undamped natural frequency
$E_S$	= voltage source
$W_q$	= width of <i>QP20N</i>
$E_q$	= young's Modulus of <i>QP20N</i>

## Abbreviations

A/D	= Analog-to-Digital
DOF	= Degrees of Freedom
D/A	= Digital-to-Analog
DCM	= Discontinuous Current Mode
FFT	= Fast Fourier Transformation
FTO	= Fluorine-doped Tin Oxide
ITO	= Indium Tin Oxide
IDE	= Inter-digitalized electrodes
IEPE	= Integrated Electronic Piezo Electric
MEMS	= Micro Electro-Mechanical System
MFC	= Micro Fiber Composite
PV	= Photovoltaic
PCB	= Printed Circuit Board
QP	= Quick Pack
RLC	= Resistance-Inductor-Capacitor
SC	= Switched-Capacitor
SSHI	= Synchronized Switch Harvesting on Inductor
TCO	= Transparent Conductive Oxide