Portable Power Scavenging from Structural Vibrations using Autonomous Self-Powered Device

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We propose a digital autonomous power scavenger with a microprocessor. The proposed system is a completely self-powered one that does not require any external power supply at all, and can thus be used portably at any site. Nevertheless, the digital approach enables the power scavenger to be programmable and thus, it affords some versatility with regard to control schemes. The proposed digital-autonomous system is much more advanced and progressive than clumsy analog-autonomous ones. It can be implemented in multiple-input multiple-output systems to scavenge electrical power from even complicated structural vibrations. We determined the value of the storage capacitance that gives the best balance between scavenging power and consumed power.

Key Words: Power Scavenging, Self-Powered, Energy Harvesting, Portable Generation

Nomenclature

- \(B_p\): input matrix
- \(C_p\): constant-strain capacitance matrix
- \(C_s\): storage capacitor for scavenged power
- \(D\): damping matrix
- \(F\): positive feedback gain
- \(K\): constant-charge stiffness matrix
- \(M\): mass matrix
- \(S_c\): switching criteria \((\equiv -F_{11}\dot{\eta}_1 - F_{12}\dot{\eta}_2)\)
- \(u_p\): elongation of piezoelectric transducer
- \(\hat{u}\): displacement vector of beam
- \(V_p\): voltage applied to transducer
- \(V_{sen}\): voltage of piezo-sensor
- \(\hat{w}\): external force vector
- \(\eta\): modal displacement vector
- \(\eta_1\): first modal displacement
- \(\zeta\): modal damping coefficient
- \(\omega_k\): natural frequency of \(k\)-th mode
- \(\hat{\cdot}\): estimated value by Kalman filter

1. Introduction

Power scavenging (or energy harvesting) is a process by which energy is captured from various sources, such as solar power, tidal power, piezoelectricity, thermoelectricity and kinematic energy, and stored for later use. Power-scavenging techniques are expected to be of vital importance in the future, when fossil fuel reserves will exhaust completely. Among the various sources mentioned above, this study focuses on power scavenging from vibrating structures using piezoelectricity. Anton and Sadano1) reviewed investigations of the piezoelectric power-scavenging techniques. Ottman et al.2) investigated an adaptive DC-DC converter to maximize the power output from piezoelectric materials. Lesieutre et al.3) discussed the damping associated with scavenging electrical power from a mechanically excited piezoelectric structure. Cornwell et al.4) proposed an approach for improving power output by using a tuned auxiliary structure. Kim et al.5) discussed structural factors to maximize the electrical power output in relation to given constraints. Makihara et al.6) proposed effective energy harvesting with a novel circuit having only two rectification diodes.

Thus far, analog self-powered autonomous systems have been proposed.7−9) These systems do not require any external power supply, neither any external control-authority. However, analog circuit systems are very awkward in practice (e.g., difficult to tune various parameters) and not programmable at all. In addition, analog systems cannot handle situations wherein certain parameters are to be changed on account of modifications to the systems.

2. Study Objectives

To solve the problems aforementioned in analog systems, we developed a digital self-powered autonomous power scavenger featuring sophisticated controls. This system consists of a programmable digital processor, a piezoelectric transducer, an inductor, and a selector switch. In particular, the self-powered processor changes the electric switch...
automatically in sync with the vibration phase, and therefore the unit can achieve autonomous power scavenging. Remarkably, this multifunctional and self-controlled processor is driven only by the voltage of the piezoelectric transducer, and therefore this processor-piezoelectric control unit is completely isolated in terms of power flow. In other words, no external power is required to activate the sensors, processors, switches, and transducers that will in turn scavenge electrical power from complicated multiple-modal vibrations. The piezoelectric transducer works as a semi-active actuator and as a power supply to drive the digital processor.

Our proposed digital self-powered autonomous system affords several significant advantages over conventional systems. Firstly, as compared to awkward analog self-powered systems, mentioned above as being impractical, this digital self-powered system is programmable and can thus be easily used to implement any type of control schemes and to properly tune various parameters. Therefore, this autonomous system is applicable to even complex multiple-input multiple-output (MIMO) systems. The significant and clear difference between sophisticated vibration controls and simple ones, including their definition, is elaborately described in reference. 10

Secondly, this semi-active system possesses the same advantages as do semi-active methods, in that it is highly effective and has excellent stability (with no chance of spillover instability), thus affording excellent control reliability in practice. We adopt the energy-recycling semi-active approach 11−13 in light of its good reliability and power efficiency. The energy-recycling method inherently possesses power-scavenging and energy-confinement mechanisms, 14 making it superior to conventional semi-active methods for various applications. 15, 16

Thirdly, the proposed system can be used portably at various sites even without external power. Many structures in sparsely settled regions are subject to vibrations; however, they cannot be used with an external power-supply because of considerations such as energy-efficiency and difficulties involved in bothersome wiring, such as in space structures, long bridges, constantly streaming factory walls, and acoustically insulated walls alongside highways and high-speed railroads.

Because our proposed power scavenger is autonomous, multifunctional, and easily adaptable to various applications, we strongly expect that it will find many practical applications to automatically scavenge electrical power from various structural vibrations.

3. Digital Self-powered System

3.1. Electrics

Figure 1 shows the power flow and control stream of the digital self-powered system. The power-scavenging section, consisting of diodes, can store electrical power, and it supplies this power to the microprocessor. A storage capacitor, $C_s$, is connected to the piezoelectric transducer so as to collect vibrational energy. By using the sent power, the processor is driven. The connection of the storage capacitor and the electric load (red line in Fig. 1 indicates the power-scavenging mechanism. Note that when the vibration becomes large, the scavenged power increases, and accordingly, the digital processor enters a wake mode and scavenges electrical power from the vibration. In contrast, when the vibration becomes small, the scavenged power decreases, and accordingly, the digital processor enters a sleep mode and waits. In this manner, the digital processor scavenges power according to the magnitude of the vibration, which is thought to be quite a rational behavior. Figure 2 shows the digital processor inside the central processing unit (CPU) board. The processor contains several hardware modules such as an analog/digital (A/D) converter and a digital/analog (D/A) converter, and it can perform software calculations.

Fig. 1. Power flow and control stream of digital self-powered system.

Fig. 2. Digital processor inside CPU board.

3.2. Mechanics

The experimental mechanical system (see Fig. 3) consists of a cantilevered beam, a piezoelectric transducer, a pantograph-type displacement-magnification mechanism, piezoelectric sensors, a vibration shaker, an added mass, and an experimental platform. The pantograph-type
displacement-magnification mechanism, attached between the beam and the upper side of the platform, is used to amplify the displacement. Piezoelectric sensors are attached at the beam’s base. Some other measuring instruments, a laser displacement sensor and a load cell, are arranged around the system. These measuring instruments are only used for record, and not used for the feedback control. The natural frequency of the mechanical motion with the piezoelectric transducer at constant electric charge is 24.4 Hz, and that at constant voltage is 22.5 Hz.

Fig. 3. Whole view of mechanical system.

3.3. Controller and structure with piezoelectric transducer

A piezoelectric transducer comprises multiple layers of a piezoceramic material, and it generates an axial force. The relation among the tensile load exerted on the transducer, elongation $u_p$ of the transducer, voltage $V_p$, and electric charge $Q$ can be written as

$$f = k_p u_p - b_p Q, \quad V_p = -b_p u_p + Q/C_p^S.$$  

(1)

Now, let us consider an $l$-DOF structure having $m$ piezoelectric transducers for the purpose of deriving generalized equations. An equation of motion for the structure with piezoelectric transducers can be written as

$$M \ddot{u} + D \dot{u} + K u = B_p \ddot{Q} + \dot{w}.$$  

(2)

To express Eq. (1) in vector-matrix form, we transform the scalar equation to

$$\ddot{V}_p = -B_p^T \ddot{u} + C_p^{-1} \dot{Q}.$$  

(3)

In modal coordinates, the equation of motion is expressed as

$$\ddot{\eta} + \Xi \ddot{\eta} + \Omega \ddot{\eta} - \Phi^T B_p \ddot{Q} - \Phi^T \dot{w} = 0,$$  

(4)

and the voltage equation is written as

$$\ddot{V}_p = -B_p^T \Phi \ddot{\eta} + C_p^{-1} \ddot{Q},$$  

(5)

where

$$\Phi \equiv [\phi_1, \phi_2, \ldots, \phi_l], \quad \Omega \equiv \text{diagonal}[\omega_k^2],$$  

$$\Xi \equiv \text{diagonal}[2\alpha_k \omega_k], \quad (1 \leq k \leq l).$$  

(6) (7)

Equations (4) and (5) can be transformed to

$$\ddot{z} = A \ddot{z} + B \dddot{Q} + E \ddot{w},$$  

(8)

$$\ddot{V}_p = C \ddot{z} + D \dddot{Q},$$  

(9)

where

$$z \equiv [\eta^T, \dot{\eta}^T]^T, \quad A \equiv \begin{bmatrix} 0 & I \\ -\Omega & -\Xi \end{bmatrix}, \quad B \equiv \begin{bmatrix} 0 \\ \Phi^T B_p \end{bmatrix},$$  

(10)

$$C \equiv -B_p^T \Phi, \quad D \equiv C_p^{-1}, \quad E \equiv \begin{bmatrix} 0 \\ \Phi^T \end{bmatrix}. \quad (11)$$

Equation (8) indicates that well-developed linear control theories could be applied, if $\dddot{Q}$ is directly controlled, for example, by using an electric charge supplier. In the linear quadratic regulator (LQR) control theory, $\dddot{Q}$ is controlled as follows:

$$\dddot{Q} = \dddot{Q}_T \equiv -F \ddot{z},$$  

(12)

where $F$ is the feedback matrix determined in the standard LQR scheme.

3.4. Control scheme in digital processor

The structure has multimodal vibrations; however, as a modal truncation to facilitate effective estimation, we implemented the reduced modal estimation of a single-degree-of-freedom (SDOF) system. The Kalman filter for the SDOF system is thus derived in our digital self-powered system, which is the same as in the experiment. Control is achieved by using estimated values of the modal velocity and displacement. Equation (8) can be transformed to

$$\ddot{z}_1 = A_1 \ddot{z}_1 + B_1 Q + E_1 \ddot{w}, \quad \ddot{z}_1 \equiv [\eta_1, \dot{\eta}_1]^T.$$  

(13)

The suffix 1 indicates that an SDOF system is being considered, and the sensor equation can be written as

$$V_{sen} = C_1 \ddot{z}_1.$$  

(14)

The Kalman filter for estimating $\ddot{z}_1$ is

$$\ddot{z}_1 = \mathbf{A}_1 \ddot{z}_1 + \mathbf{B}_1 Q + \mathbf{\Gamma}_1 (V_{sen} - C_1 \ddot{z}_1),$$  

(15)

where the filter gain $\mathbf{\Gamma}_1$ is obtained from the solution of the Ricatti equation.

Following the energy-recycling strategy, switching criteria, $S_c \equiv -F_{11} \dot{\eta}_1 - F_{12} \dot{\eta}_1$, are needed for the switching operation in our autonomous program. The criteria are calculated using the estimated values ($\hat{\eta}_1$ and $\dot{\hat{\eta}}_1$). Here, $F_{11}$ and $F_{12}$ appear similar to the feedback coefficients of $Q_T$ in Eq. (12) and are derived by the same scheme as is $Q_T$. However, their meanings in control are different, because our control approach is semi-active control and not the active
control. An interesting and insightful discussion of the difference between the optimal input for active controls and the switching criteria (a target value) for semi-active controls is presented in reference.\textsuperscript{14} For the digital implementation of our self-powered programming, a switching strategy using switching criteria is constructed as

\[
\begin{align*}
\text{when } S_c > 0, & \quad \text{Switch point 1 is on}, \\
\text{when } S_c < 0, & \quad \text{Switch point 2 is on.} 
\end{align*}
\]

(16)

When some power scavenged from vibrations is supplied to the microprocessor, the processor enters a wake mode. In conclusion, the programming code is created to implement this circuit switch determination and the aforementioned Kalman filter to estimate the modal velocity and displacement. Finally, the entire program code is programmed into the digital processor.

3.5. Operating procedure of digital processor

The digital processor (i) activates with the electrical power supplied by the power-scavenging mechanism, (ii) collects data pertaining to structural vibrations from the piezo-sensors, (iii) calculates the modal estimation using the Kalman filter, (iv) calculates its switching criteria, (v) activates the switch to reverse the voltage polarity of the piezoelectric transducer when the switching criteria shifts, and (vi) monitors the transducer with the shifted voltage polarity that works as an actuator to scavenge electrical power from structural vibrations. All of these steps are carried out in each clock cycle.

In the processor, the continuous Kalman filter is updated by the fourth-order Runge-Kutta method in the processor instead of by a discrete formula, because the estimation precision is of great importance in systems subject to large ambient noise.

4. Experiments

4.1. Electronic components of power scavenger

A piezoelectric transducer (PSt 1000/10/200-VS18, Piezomechanik GmbH.) was used for the self-powered system with the pantograph-type displacement-magnification mechanism. The multifunctional digital processor consists of a 16-bit processing component, an internal clock oscillator, a RAM, a flash ROM for storing programs, 10-bit A/D converters, digital output ports, a hardware integer multiplier/divider, and a real-time clock. A step-down DC/DC converter was implemented in the electric circuit. Piezoelectric sensors (C-91H, Fuji Ceramics Co.) were used to detect the state of vibration.

4.2. Results

We carried out experiments to validate our proposed power scavenger. To estimate the modal velocity and displacement, the Kalman filter in Eq. (15) was used. In the actual implementation, the value of electric charge was neglected, because it is typically constant in our switching control and because it is difficult to detect. Furthermore, from the viewpoint of vibration control, the value of the velocity, which is obtained by taking the derivative of the displacement, is much more important than the value of the displacement itself, and therefore, the displacement shift due to the neglected charge is practically insignificant. \( F_{11} \) was thus set to be 0.

![Fig. 4. History of power scavenging (C_s = 0.1 \mu F).](image)

![Fig. 5. History of power scavenging (C_s = 47 \mu F).](image)

We compared the scavenged voltage in \( C_s \), which is a simple electric load, in order to clearly compare the scavenging performance. We present time histories of piezoelectric voltage and scavenged voltage in Figs. 4, 5, and 6. The piezoelectric voltage is informative reference for the purpose of confirming switching and voltage-inversion timing. These figures indicate that 0.1 \( \mu F \) is too small to store electrical
power, because the value of the scavenged voltage fluctuates. As seen in Fig. 5, capacitance value $47 \mu F$ is too large to full electric power in the storage capacitor, considering the scavenging capability of the system. As seen in Fig. 6, a capacitance value of $1.0 \mu F$ provides good balance between scavenging power and consumed power for this self-powered system.

To analyze the influence of storage capacitor on scavenging, we carried out extensive experiments for various capacitor. Figure 7 shows the maximum value of the scavenged voltage in $C_s$. For comparison with our self-powered system, a powered system which digital processor was driven by the supplied external power was also investigated. This figure shows that the scavenged voltage of the powered system is greater than that of the self-powered system. This fact is reasonable, because some amount of power is consumed to drive the digital processor. The figure also shows that the scavenging system with $C_s = 1.0 \mu F$ has the best performance.

The line of the powered system (Power supply line in Fig. 7) is thought to be 100% efficiency of power scavenging, because the digital processor was driven by the external power. In light of scavenged voltage, our portable power scavenger (Self-powered line in Fig. 7) has at least 60% efficiency of power scavenging. This is quite a striking performance in the self-powered power-scavenging field. The DC/DC converter and other electronic devices are sharply dependent on the range of input voltage, and further profound investigation of scavenging efficiency is our future work.

We are also proposing a vibration suppressor on the basis of the digital-controller approach\(^1\), which at first sight, looks a similar sort to the power scavenger proposed in this paper. However, there are crucial distinctions between this portable power scavenger and the vibration suppression unit. Especially, since electric loads in power scavengers outflow the substantial amount of electrical power, they can easily upset the power equilibrium and can produce systemic paralysis. The power flow thus exercises a sensitive influence on the energy-closed systems. Therefore, it is necessary to take account of the power flow of electric loads, differently from vibration suppressors. In this paper, we carefully evaluated the power balance and clarified the scavenging performance varying the value of storage capacitance in Figs. 4-7. The load flow issue is of vital importance to the best operation of the proposed power scavenging system, leading to the significant difference from the digital vibration-suppression unit.

5. Conclusions

We propose a digital self-powered autonomous power scavenger with a digital processor. Our invented unit is a completely self-powered unit that does not require any external power-supply at all. Despite this, the digital and autonomous approach enables the power scavenger to be programmable and thus, versatile in control schemes. The proposed system constitutes a vast improvement over conventional analog-autonomous systems. It can be implemented in MIMO systems to scavenge electrical power from even complicated structural vibrations. We carried out power-scavenging experiments using our system to verify its effectiveness. We determined the value of storage capacitance that gives the best balance between scavenging power and consumed power. Our experimental results show that the proposed system is quite versatile and accordingly, is likely to find diverse applications. We expect that it will find applications to various power-scavenging systems, and we hope that it will serve as a starting point for further studies in this field.

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