Self-Powered Low Power Signal Processing

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Abstract— **A chip has been designed and tested to demonstrate the feasibility of operating a digital system from power generated by vibrations in its environment. Calculations show that power on the order of 800 μW can be generated. Tests verify 1 MHz operation of a subband filter chip using only 10's of μW of power.**

I. Introduction

Portable systems that depend on batteries have a limited operating life and are prone to failure at inconvenient times. We propose a system as in Figure 1, consisting of a generator to create a DC voltage, a DC/DC converter to set the voltage to meet the desired performance, and a DSP which performs some computation. The desired voltage is set by the rate at which the DSP is to produce results.

II. Power Generation

The sources of ambient energy available to the portable or embedded system depend on the application. Examples include light or electromagnetic fields, thermal gradients, fluid flow, and mechanical vibration. A generator based on transducing mechanical vibrations has some distinct advantages: it can be enclosed and protected from the outside environment, it functions in a constant temperature field, and it can be activated by a person (by shaking it, for example). However, it has moving parts and hence less long-term reliability.

Williams and Yates propose an inertial electromechanical generator [1]. This device consists of a mass m connected to a spring, the whole mounted within a rigid housing. As the housing is vibrated, the mass moves relative to the housing and energy is stored in the mass-spring system.

Assuming a linear system, an analytic formula for the power transferred by a sinusoidal excitation, $y(t) = Y_0 \cos(\omega t)$, of the generator housing is presented in [1]. However, to estimate the amount of power that can be obtained and to gain insight into generator design it is useful to look at the frequency domain representation. The power $p(t)$ is the product of the applied force and the velocity of the mass. From this we can derive the Fourier transform of the power:

$$P(j\omega) = -m\omega^2 Y(j\omega) * \left(\frac{-j\omega^3}{\omega_0^2 - \omega^2 + 2j\zeta\omega_0\omega}\right) Y(j\omega) \quad (1)$$

where ζ and ω_0 are the damping factor and natural frequency (radians/s) for a second order system respectively.

Figure 2 shows two output power spectra for a bandpass input vibration centered on 5 Hz. The top plot shows the power for a natural frequency f_0 of 1 kHz, much greater than the excitation frequency. The DC component of the power is almost zero in this case. The bottom plot shows the power for a natural frequency of 5 Hz and the DC power is much greater. For maximum power, one would like ω_0 to be close to the expected input frequencies. This is often not practical, especially if the generator must have a small mass and displacement and the vibration frequencies are very low (corresponding to human movement). Even in the first case in the figure, the DC power is approximately 800 μW - enough to power ultra low power DSP systems.

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III. DC/DC Converter Chip

To demonstrate the feasibility of a self-powered system, an integrated circuit containing a switching DC/DC converter and an FIR filter was constructed. It was powered by the generator assembly depicted in the bottom half of Figure 3. The output of the generator was transformed to a higher voltage that could be rectified by diode D1 onto the capacitor C1. Voltage V_{in} is the input voltage to the regulator.

The bootstrapping circuit is shown in the top half of Figure 3. At startup, the controller supply V_{dd} receives its power from the backup source V_{bk}, either a battery or a capacitor. After the controller has converted V_{in} to the desired level, BOOT goes high and V_{dd} is connected to the generated voltage. If V_{out} drifts too far from the desired value the controller will switch itself back to the backup supply.

Figure 4 shows the controller feedback loop, similar to [2], [3]. The DSP rate command, f_{clk}, is compared to the VCO output f_{vco}. The VCO is a ring consisting of the DSP adder critical path padded with a few inverters and is supplied by the regulated output voltage. The converter is a Buck converter with very small P and N FETs (1200 μm and 300μm) controlled by a PWM waveform with 6 bit resolution. A new duty cycle is determined from the 2 bit frequency error. The modulated V_{in} signal is then passed through an LC lowpass filter, external to the chip, to produce V_{out}. The FIR filter is a well-known subband filter [4].

IV. Test Results

For test purposes, the generator consisted of a miniature moving coil loudspeaker used as a microphone. An identical loudspeaker driven by a signal generator provided the input stimulus. This generated a V_{in} of approximately 1 V. The full system including the DSP was observed to work from 100 kHz up to 1 MHz for V_{out} from about 0.85 V up to 0.97 V.

The output response to a step change in V_{in} is shown in Figure 5. After some initial ringing (~40 ms), the output settles except for small low frequency ripples at the far right of the trace. A limit cycle in the controller due to the low resolution error feedback causes the PWM to oscillate around the correct value.

Figure 6 shows the bootstrapping circuit in operation. When BOOT goes high, V_{dd} rises to the higher regulated value, and the frequency of the PWM output increases, as expected. The V_{dd} glitch is due to timing mismatch in the switch gate signals. The test chip parameters are summarized in Table I. A die photo is shown in Figure 7.

References

[1] C.B. Williams and R.B. Yates, "Analysis of a micro-electric generator for microsystems," in *Transducers '95/Eurosensors IX*, 1995.

[2] Vadim Gutnik and Anantha Chandrakasan, "An efficient controller for variable supply–voltage low power processing," in *Symposium on VLSI Circuits*, 1996.

[3] Gu-Yeon Wei and Mark Horowitz, "A low power switching power supply for self-clocked systems," in *1996 ISLPED*, 1996, pp. 313–318.

[4] B. Gordon and T. Meng, "A 1.2 mW video-rate 2-D color subband coder," *IEEE JSSC*, vol. 30, no. 12, pp. 1510–1516, December 1995.

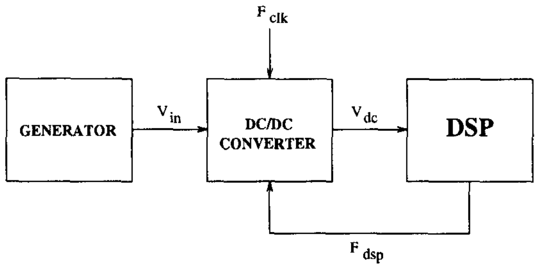

Fig. 1. System Block Diagram.

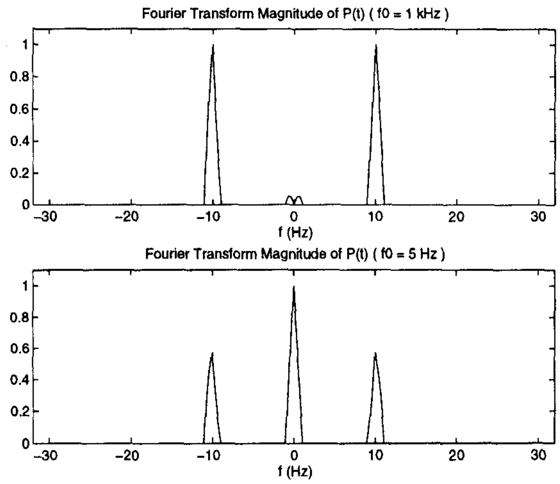

Fig. 2. Spectrum of Power Signal.

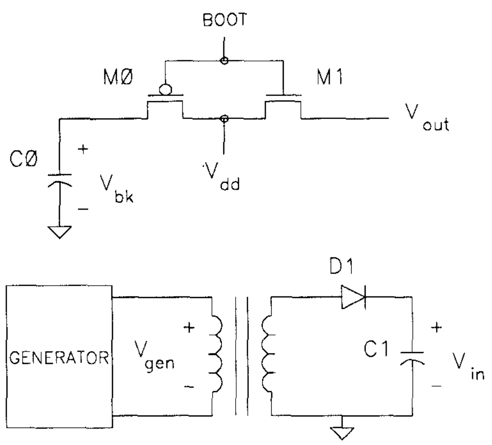

Fig. 3. Generator and Bootstrap Circuit Schematic.

Area	2609 μm x 2609 μm
Transistor Count	5003
Process	0.8 μm CMOS
Controller Power	5.71 μW (f_{clk} = 500kHz, V_{dd} = 1V)
Subband Filter Power	4.75 μW (f_{clk} = 500kHz, V_{out} = 1V)
Switch Drive Power	7.50 μW (V_{in} = 1.07V)

TABLE I
TEST CHIP SPECIFICATIONS.

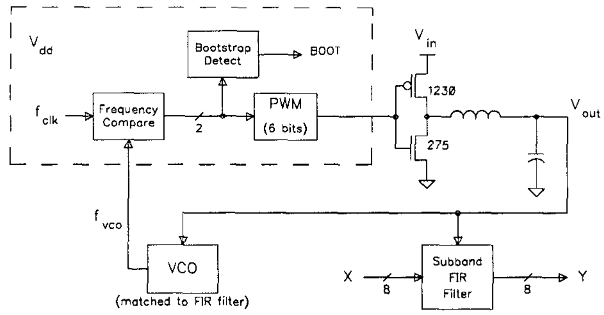

Fig. 4. Regulator Feedback Loop.

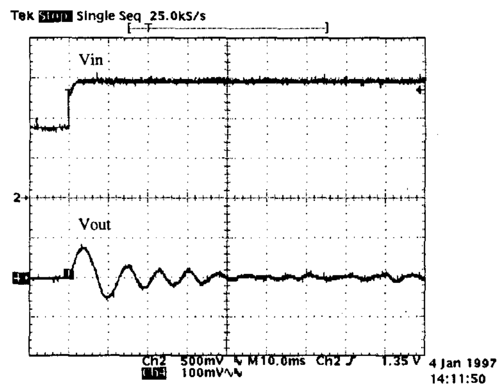

Fig. 5. Step Response.

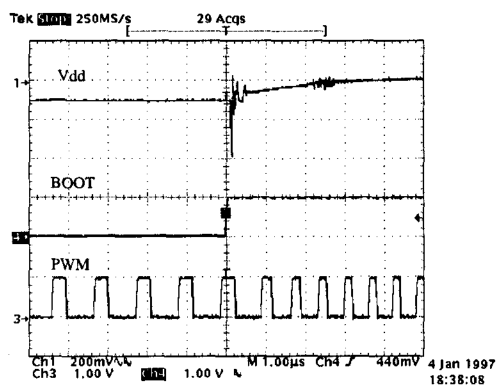

Fig. 6. Bootstrapping.

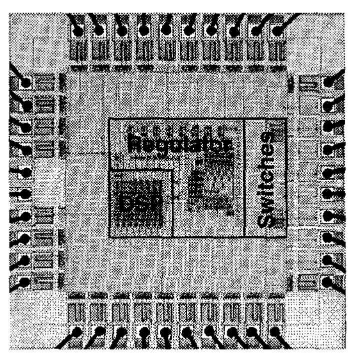

Fig. 7. Die Photo.