

Aircraft Structures Take Advantage of Energy Harvesting Implementations

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This article describes the elements that make up an energy harvesting power source, including new ICs for power collection and system management

Sometimes a major incident is necessary before mankind's awareness is pushed to the forefront. How many of us remember that fateful day back on April 28th, 1988, when

Aloha Airlines Flight 243 broke apart? In short, approximately 23 minutes after takeoff, a small section on the left side of the roof ruptured. The resulting explosive decompression tore off a large section of the roof, consisting of the entire top half of the aircraft skin extending from just behind the cockpit to the forewing area. The electrical wiring from the nose gear to the indicator light on the cockpit instrument panel was also severed. As a result, the light did not illuminate when the nose gear was lowered, so the pilots had no way of knowing if it had fully extended. Fortunately, the crew was able to perform an emergency landing whereupon they deployed the aircraft's evacuation slides and evacuated passengers from the aircraft quickly. In all, 65 people were reported injured, 8 seriously.

A miraculous ending for this set of passengers for sure, but an investigation by the U.S. National Transportation Safety Board (NTSB) concluded that the accident was caused by metal fatigue exacerbated by crevice corrosion (the plane operated in a coastal environment, with exposure to salt and humidity). The root cause of the problem was failure of an epoxy adhesive used to bond the aluminum sheets of the fuselage together when the Boeing 737 was manufactured. Thus, water was able to enter the gap where the epoxy failed to bond the two surfaces together properly and started

the corrosion process. The final conclusion was that the age of the aircraft was the key mechanism in the accident, and that in order to prevent the likelihood of future occurrences, all aircraft should receive regular fuselage maintenance checks going forward.

Aircraft Health Monitoring

There can be no doubt that the structural fatigue of today's large fleet of aircraft is a serious issue and needs to be addressed. Fortunately, it is. This is being accomplished through more inspections, through improved structural analysis and tracking methods and by incorporating new and innovative ideas for assessing structural integrity. This is sometimes referred to as "health monitoring of aircraft." This process incorporates sensors, artificial intelligence and advanced analytical techniques to produce real time and continual health assessment.

Acoustic emission detection is a well-established method of locating and monitoring crack development in metal structures. It can be readily applied for the diagnosis of damage in composite aircraft structures. A clear requirement is a level form of "go," "no go" indications of structural integrity or immediate maintenance actions. The technology comprises low profile detection sensors using piezoelectric wafers encapsulated in polymer film and optical sensors. Sensors are bonded to the structure's surface and enable acoustic events from the loaded structure to be located by triangulation. Instrumentation is then used to capture and parameterize the sensor data in a form suitable for low-bandwidth storage and transmission.

Thus, although wireless sensor modules

are often embedded in various airplane sections for structural analysis, wings or fuselage, for example, powering them can be cumbersome. Therefore, these sensor modules are more convenient and efficient when powered wirelessly, or even self-powered. In an aircraft environment there are a number of “free” energy sources available to power such sensors. Two obvious methods are thermal energy harvesting and piezoelectric vibrational energy harvesting. Each has pros and cons and will be discussed in more detail.

Energy Harvesting Basics

Transducers that create electricity from readily available physical sources such as temperature differentials (thermoelectric generators or thermopiles), mechanical vibration or strain (piezoelectric or electromechanical devices) and light (photovoltaic devices) are viable sources of power for many applications. Numerous wireless sensors, remote monitors, and other low-power applications are on track to become near “zero” power devices using only harvested energy.

Even though the concept of energy harvesting has been around for a number of years, the implementation of a system in a real world environment has been cumbersome, complex and costly. Nevertheless, examples of markets where an energy harvesting approach has been used include transportation infrastructure, wireless medical devices, tire pressure sensing, and building automation.

A typical energy scavenging configuration or system (represented by the four main circuit system blocks shown in Fig. 1), usually consists of a free energy source. Examples of such sources include a thermoelectric generator (TEG) or thermopile attached to a heat-generating source such as an aircraft engine, or a piezoelectric transducer attached to a vibrating mechanical source such as an aircraft airframe or wing.

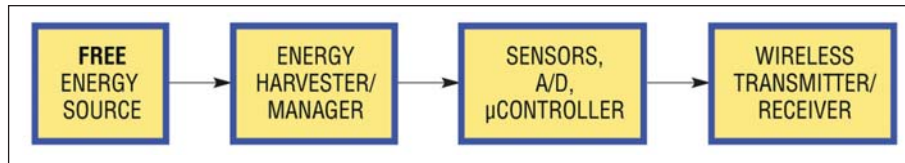


Figure 1 · The four main blocks of a typical energy-scavenging system.

In the case of a heat source, a compact thermoelectric device can convert small temperature differences into electrical energy. And where vibration or strain is available, a piezoelectric device can convert these small vibrations or strain differences into electrical energy. In either case, the electrical energy produced can be converted by an energy harvesting circuit (the second block in Fig. 1) and modified into a usable form to power downstream circuits. These downstream electronics usually consist of some kind of sensor, an analog-to-digital converter and an ultralow power microcontroller (the third block in Fig. 1). These components can take this harvested energy, now in the form of an electric current, and wake up a sensor to take a reading or a measurement and then make this data available for transmission via an ultralow power wireless transceiver—represented by the fourth block in the circuit chain shown in Figure 1.

Each circuit system block in this chain, with the possible exception of the energy source itself, has had its own unique set of constraints that have impaired economical viability until now. Low cost and low power sensors and microcontrollers have been available for a couple of years; however, it is only recently that ultralow power transceivers have become commercially available. Nevertheless, the laggard in this chain has been the energy harvester.

Existing implementations of the energy harvester block typically consist of low performing discrete configurations, usually comprising 30 or more components. Such designs have low conversion efficiency and high quiescent currents. Both of these defi-

ciencies result in compromised performance in end-systems. The low conversion efficiency increases the amount of time required to power up a system, which in turn increases the time interval between taking a sensor reading and transmitting the data. A high quiescent current limits how low the output of the energy-harvesting source can be, since it must first overcome the current level needed for its own operation before it can supply any excess power to the output.

Energy Harvesting Transducers and ICs

The core component of a thermoelectric device is a thermocouple, which consists of an n-type and a p-type semiconductor connected by a metal plate. Electrical connection at the opposing ends of the p- and n-type material complete an electric circuit. Thermoelectric generation (TEG) occurs when the couple is subjected to a thermal gradient, in which case the device generates a voltage and causes current to flow, thereby converting heat into electrical power by what is known as the Seebeck effect. A thermoelectric module is then formed from arrays of these thermocouples connected in series. If heat is flowing between the top and bottom of the module, a voltage will be produced and an electric current will flow.

In the case of a typical airplane engine, its temperature can vary anywhere from a few 100°C to 1,000 to 2,000°C. Although most of this energy is lost in the form of mechanical energy (from combustion and thrust), a portion is dissipated purely as heat. Since the Seebeck effect is the underlying thermodynamic phenomenon

that converts thermal heat to electric power, the main equation to take into consideration is:

$$P = \eta Q$$

where P is electrical power, Q is heat and η is efficiency.

Larger TEGs that use more heat, Q , produce more power, P . Similarly, the use of twice as many power converters naturally produces twice the power, given that they can capture twice the heat. Larger TEGs are created by putting more P-N junctions in series; however, while this creates more millivolts per temperature increment (mV/dT), it also increases the series resistance of the TEG. This increased resistance limits the power available to the load. Therefore, depending on the application requirements, it is sometimes better to use smaller TEGs in parallel rather than using a larger TEG. Regardless of the choice, TEGs are commercially available from a number of suppliers, including Tellurex Corp.

Piezoelectricity can be generated by applying stress to an element, which in turn creates an electric potential. The piezoelectric effect is reversible in that materials exhibiting the direct piezoelectric effect—the production of an electric potential when stress is applied—also exhibit the reverse piezoelectric effect—the production of stress and/or strain when an electric field is applied.

In order to optimize a piezo transducer, one needs to characterize the source for vibration frequency and displacement. Once these levels have been determined, a piezo manufacturer can design a piezo that is mechanically tuned to the specific vibration frequency and size it to provide the necessary amount of power. The vibration in the piezo material activates the Direct Piezo effect, which results in the accumulation of charge on the output capacitance of the device. This is usually pretty small so the AC open circuit voltage

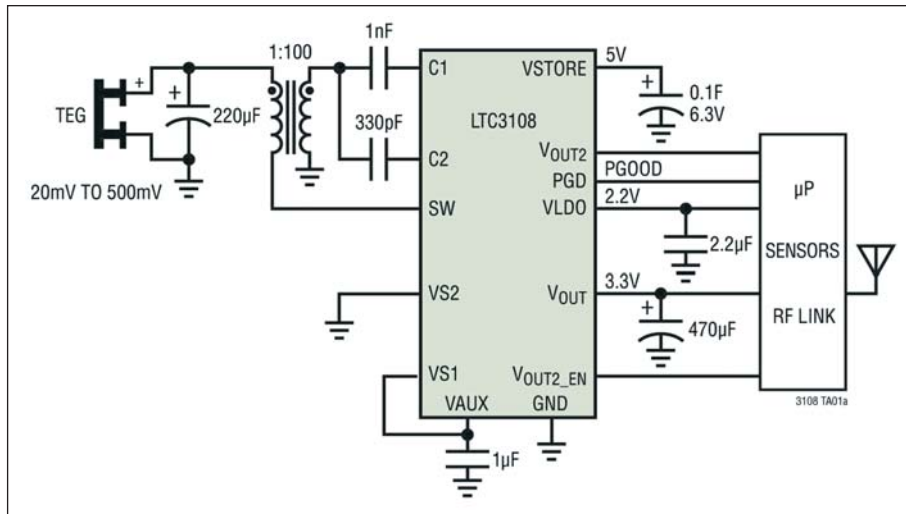


Figure 2 · The LTC3108 used in a wireless remote sensor application powered from a TEG (Peltier cell).

is high—on the order of 200 volts in many cases. Since the amount of charge generated from each deflection is relatively small, it is necessary to full-wave rectify this AC signal and accumulate the cycle-by-cycle charge on an input capacitor. Once again, there are a number of piezoelectric transducers commercially available from a number of suppliers, including AmbioSystems, MIDE Technology Corp. and Advanced Cerametrics Inc.

However, what has been missing until now has been a highly integrated, high efficiency DC/DC converter solution that can both harvest and manage the energy from either a thermal or piezoelectric source. Linear Technology’s innovative LTC3108 and LTC3588-1 will greatly simplify the task of harvesting surplus energy from a variety of sources.

The recently introduced LTC3108 is an ultralow voltage step-up converter and power manager specifically designed to greatly simplify the task of harvesting and managing surplus energy from extremely low input voltage sources such as thermopiles, thermoelectric generators (TEGs) and even small solar panels. Its step-up topology operates from input voltages as low as 20 mV. This is significant since it allows the LTC3108 to

harvest energy from a TEG with as little as 1°C temperature differential—something a discrete implementation struggles to meet due to its high quiescent current.

The circuit shown in Figure 2 uses a small step-up transformer to boost the input voltage source to a LTC3108, which then provides a complete power management solution for wireless sensing and data acquisition. It can harvest small temperature differences and generate system power instead of using traditional battery power.

The LTC3108 utilizes a depletion mode N-channel MOSFET switch to form a resonant step-up oscillator using an external step-up transformer and a small coupling capacitor. This allows it to boost input voltages as low as 20 mV, high enough to provide multiple regulated output voltages for powering other circuits. The frequency of oscillation is determined primarily by the inductance of the transformer’s secondary winding and input capacitance of the LTC3108 and is typically in the range of 20 to 200 kHz.

For input voltages as low as 20 mV, a primary-secondary turns ratio of about 1:100 is recommended. For higher input voltages, a lower

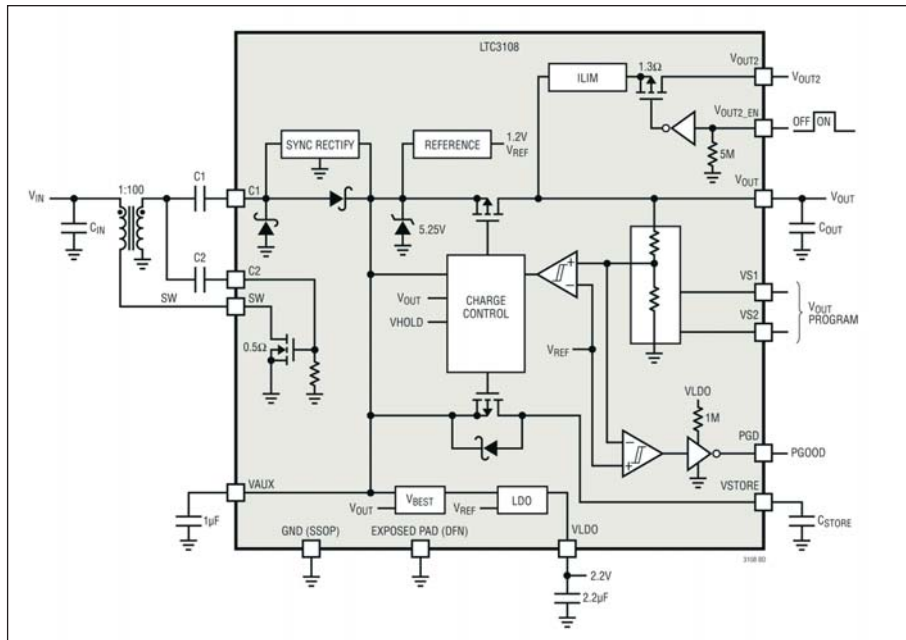


Figure 3 · The LTC3108 block diagram.

turns ratio can be used, since it will provide greater output power. These transformers are standard, off-the-shelf components, and are readily available from magnetic suppliers. Linear’s compound depletion mode N-channel MOSFET is what makes 20 mV operation possible.

As can be seen in Figure 3, the LTC3108 takes a “systems level” approach to solving a complex problem. It can convert the low voltage source and manage the energy between multiple outputs. The AC voltage produced on the secondary winding of the transformer is boosted and rectified using an external charge pump capacitor (from the secondary winding to pin C1) and the rectifiers internal to the LTC3108. This rectifier circuit feeds current into the V_{AUX} pin, providing charge to the external V_{AUX} capacitor and then the other outputs.

The internal 2.2 V LDO can support a low-power processor or other low power ICs. The LDO is powered by the higher value of either V_{AUX} or V_{OUT} . This enables it to become active as soon as V_{AUX} has charged to 2.3V, while the V_{OUT} storage capacitor is still charging. In the event of a

step load on the LDO output, current can come from the main V_{OUT} capacitor if V_{AUX} drops below V_{OUT} . The LDO output can supply up to 3 mA.

The main output voltage on V_{OUT} is charged from the V_{AUX} supply and is user programmable to one of four regulated voltages using the voltage select pins VS1 and VS2. The four fixed output voltages are: 2.35 V for supercapacitors, 3.3 V for standard capacitors and RF or sensor circuitry, 4.1 V for lithium-ion battery termination or 5 V for higher energy storage and a main system rail to power a wireless transmitter or sensors—thereby eliminating the need for multi-meg-ohm external resistors. As a result, the LTC3108 does not require special board coatings to minimize leakage, as do discrete designs where very large value resistors are required.

A second output, V_{OUT2} , can be turned on and off by the host micro-processor using the V_{OUT2_EN} pin. When enabled, V_{OUT2} is connected to V_{OUT} through a P-channel MOSFET switch. This output can be used to power external circuits such as sensors or amplifiers that do not have

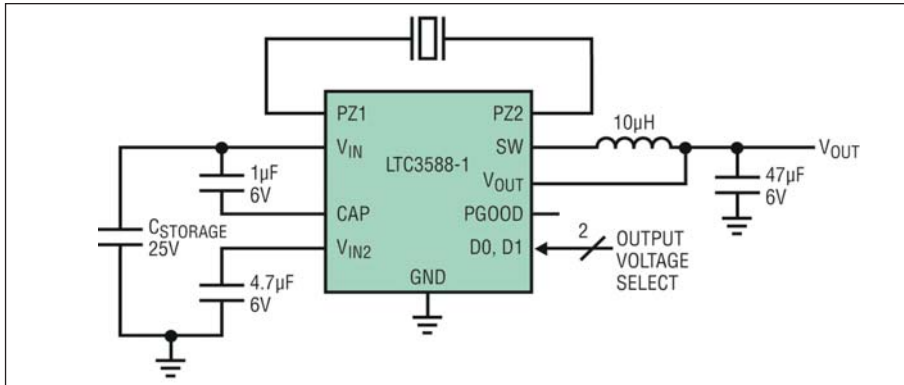


Figure 4 · The LTC3588-1 circuit schematic converts a vibration or strain source into electric current.

low power sleep or shutdown capability. An example of this would be to power a MOSFET on and off as part of a sensing circuit within a building thermostat.

The V_{STORE} capacitor may be a very large value (thousands of microfarads or even farads), to provide holdup at times when the input power may be lost. Once power-up is completed, the main, backup and switched outputs are all available. If the input power fails, operation can still continue, operating off the V_{STORE} capacitor. The V_{STORE} output can be used to charge a large storage capacitor or rechargeable battery after V_{OUT} has reached regulation. Once V_{OUT} has reached regulation, the V_{STORE} output is allowed to charge up to the V_{AUX} voltage, which is clamped at 5.3 V. Not only can the storage element on V_{STORE} be used to power the system if the input source is lost, but it can also be used to supplement the current demanded by V_{OUT} , V_{OUT2} and the LDO outputs if the input source has insufficient energy.

A power good comparator monitors the V_{OUT} voltage. Once V_{OUT} has charged to within 7% of its regulated voltage, the PGOOD output will go high. If V_{OUT} drops more than 9% from its regulated voltage, PGOOD will go low. The PGOOD output is designed as logic-level drive a microprocessor or other chip I/O and is not intended to drive a higher current

load such as an LED.

The circuit shown in Figure 4 utilizes a small piezoelectric transducer to convert mechanical vibration into an AC voltage source that is fed into the LTC3588-1's internal bridge rectifier. It can harvest energy from small vibration sources and generate system power instead of using traditional battery power.

The LTC3588-1 is an ultralow quiescent current power supply designed specifically for energy harvesting and/or low current step-down applications. It can interface directly to a piezoelectric or alternative AC power source, rectify the voltage waveform and store harvested energy in an external capacitor, bleed off any excess power via an internal shunt regulator and maintain a regulated output voltage by means of a nanopower high efficiency buck regulator.

The LTC3588-1's internal full-wave bridge rectifier is accessible via two differential inputs, PZ1 and PZ2, which rectify AC inputs. This rectified output is then stored on a capacitor at the V_{IN} pin and can be used as an energy reservoir for the buck converter. The low-loss bridge rectifier has a total voltage drop of about 400 mV with typical piezo generated currents, which are normally around 10 mA. This bridge is capable of carrying up to 50 mA of current. The buck regulator is enabled once there

	Pros	Cons
Thermal	Able to continuously supply DC power.	Temperature differentials can be difficult to implement in enclosed environments (Note 1).
Piezoelectric	Does not need to be manually charged. The aircraft provides plenty of vibrational force.	Each element has to be manually tuned to the aircraft's vibrational frequency.

Note 1: The best opportunity for temperature differential in an aircraft is between the aircraft "skin" on the inside of the cabin and the internal cabin temperature.

is sufficient voltage on V_{IN} to produce a regulated output.

The buck regulator uses a hysteretic voltage algorithm to control the output through internal feedback from the V_{OUT} sense pin. The buck converter charges an output capacitor through an inductor to a value slightly higher than the regulation point. It does this by ramping the inductor

current to 260 mA through an internal PMOS switch and then ramping it down to 0 mA through an internal NMOS switch, thereby efficiently delivering energy to the output capacitor. Its hysteretic method of providing a regulated output reduces losses associated with FET switching and maintains an output at light loads. The buck converter delivers a mini-

mum of 100 mA of average load current when it is switching.

Conclusion

With respect to the energy source choice, there are trade-offs between thermal and piezoelectric sources. The table above summarizes the pros and cons between these two methods.

With analog switchmode power supply design expertise in short supply around the globe, it has been difficult to design an effective energy harvesting system, as illustrated in Figure 1. However, the introduction of the LTC3108 and LTC3588-1 address that difficulty. With a proper transducer, these devices can extract energy from almost any source of heat or mechanical vibration, both of which are commonly found in an airplane environment. Furthermore, with their comprehensive feature sets and ease of design, they greatly simplify the hard-to-do power conversion design of an energy harvesting chain. This is good news for the designer of aircraft health monitoring systems because their high integration, including power management control and off-the-shelf external components, make them the smallest, simplest and most easy-to-use solutions available to complete the energy harvesting chain.

Author Information

Tony Armstrong, Director of Product Marketing for Linear Technology's Power Products group, joined the company in 2000. He is responsible for all aspects of the power conversion and management of products from conception through obsolescence. Prior to joining Linear, Tony held various positions in marketing, sales and operations at Siliconix Inc., Semtech Corp., Fairchild Semiconductors and Intel Corp. (Europe). He attained a BS (Honors) in Applied Mathematics from the University of Manchester, England in 1981. He can be reached at: tarmstrong@linear.com