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Wireless Telemetry for Gas-Turbine Applications

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March 2000

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ABSTRACT

Wireless telemetry technology for transmitting power and data to and from sensors located inside a gas-turbine engine is reviewed. Two scenarios are considered: a rotating sensor hardwired to a shaft-mounted, inductively-coupled system; and a stationary or rotating microsensor telemetry module. Applications of these telemetry scenarios in the gas-turbine operating environment, the types of sensor measurements, the principles of telemetry, and a review of the current state of microfabricated components for telemetry systems are given. Inductive coupling for both data and power transmission is emphasized in the first scenario. The microsensor telemetry module discussed in the second scenario would need battery power or an alternative power source. These technologies are emerging and do not represent available products. A brief list of alternative technologies for providing power is presented at the end.

INTRODUCTION

1. Principles of Telemetry

Telemetering is defined as the complete measuring, transmitting, and receiving for indicating at a distance, by electrical translating means, the value of a quantity. The measurement is made by such transducers as the resistance strain gage, thermocouple, thermistor, pressure transducer, accelerometer, etc. The transducer converts the measured quantity to an electrical signal which is then transmitted without a conductor to a receiver. The simplest telemetry system is shown in block-diagram form in Figure 1. A battery-powered RF oscillator modulates the transducer's voltage signal and passes it to an FM antenna. A remote receiving antenna captures the FM signal and demodulates it before passing it to a readout. The power to operate the transducer and oscillator must be transmitted if a battery is not present. As will be described, transmitting power more than a few centimeters is not practical in most cases.

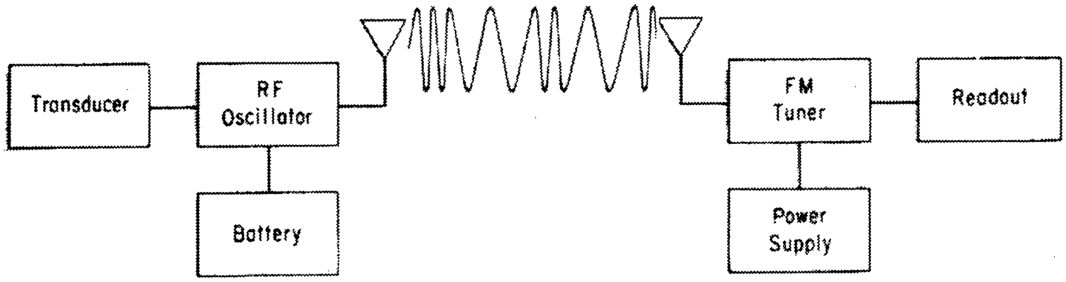


Figure 1: Block diagram of RF-telemetry system.

A generic telemetering system for transmitting between stationary frames is comprised of three basic elements: a transducer, a transmitting station, and a receiving station. A typical telemetry link is shown in Figure 2. Sometimes the transmitting station also receives data and is called a transceiver. In typical situations, the transducer's excitation voltage is supplied by a voltage regulator or oscillator. Its output voltage is used to modulate the frequency of a sub-carrier oscillator which then modulates the frequency of a radio carrier. The signal is transmitted from transmitter to receiver by means of the transmitting antenna.

A battery in the transmitting station supplies the power for the whole transmitter. For long-term installations the power can be taken from the machine on which the telemetry system is installed or provided by an induction link.

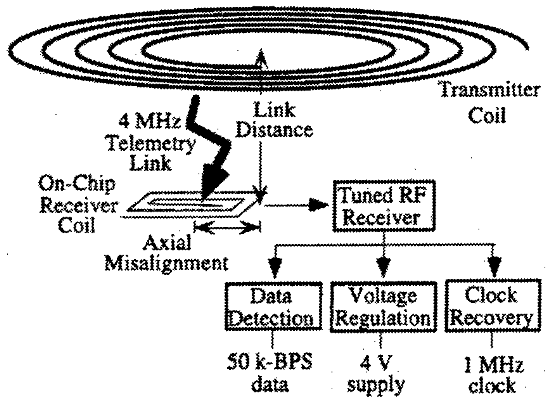


Figure 2: Typical RF-telemetry system.

At the receiving station the tuner, which is tuned to the transmitting radio frequency, receives the signal via the receiving antenna. The signal passes through a filter to remove the carrier frequency and is then recorded or displayed. The waveforms of the telemetry modulation methods generally used in short-range telemetry systems are AM, FM, pulse amplitude, pulse duration, or pulse code. Examples are shown in Figure 3.

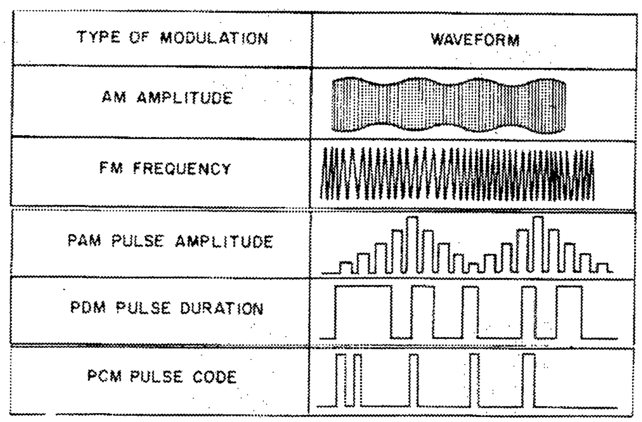


Figure 3: Example modulation techniques used in telemetering systems.

A simple transmitter contains resistors, capacitors, inductors, oscillators, transistors, batteries, antennae, and the wiring necessary to connect the components.

When the transducer is mounted on a rotating reference frame, an inductively coupled antenna pair can be used to transmit both data and power[1]. A schematic diagram of this system is given in Figure 4. The rotary transformers are usually a pair of concentric loops of wire separated by a fraction of a centimeter. The rotating coil is mounted on the end of the shaft; the stationary coil is connected to the data-acquisition system. This system requires access to the shaft. The figure shows a system employing separate coils for data and power; though it is possible to transmit both power and data with a single pair of coils.

[1] This technique is also used to transmit data and power to and from sensors on the stationary reference frame, for example, implants in the medical field.

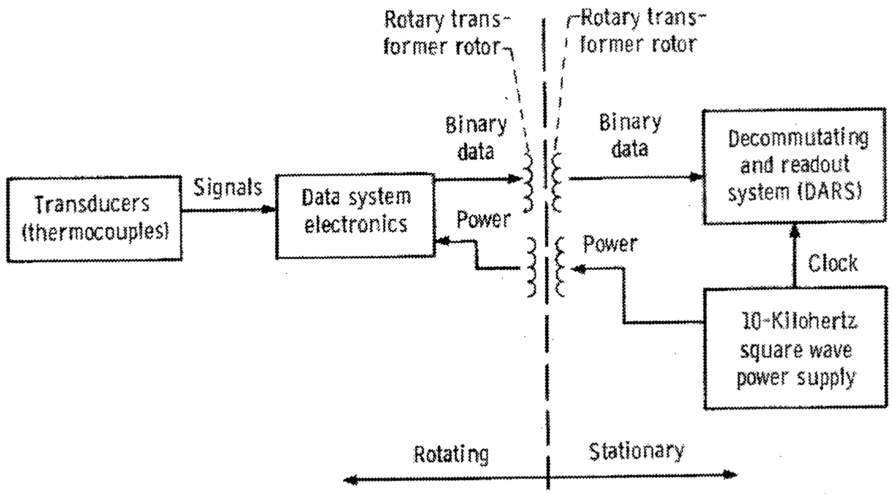


Figure 4: Block diagram of inductively-coupled, antenna pair for telemetering temperature from the rotating to the stationary frame.

2. History of Telemetry for Rotating Machinery

Before radio telemetry was developed, slip rings were used to transmit electrical signals from rotating shafts to recording equipment. Although slip rings were and are effective, assembling the equipment can be expensive. The end of the rotating shaft must also be available to install the slip rings or the slip rings must be installed in series between shafts. If the sensor wires must pass bearings along the shaft, it is sometimes impossible to make the measurement.

The solution to the slip-ring problem was to develop some kind of packaged instrumentation that could be used on almost any kind of existing shaft requiring no custom fitting. The package would have to be small and require a minimum of power to operate. The development of transistors and integrated circuits and their use in miniature radio transmitters was a step forward. With a small transmitter nominally one cubic inch in volume and a battery occupying another cubic inch, it was possible to transmit a signal from almost any size shaft with no shaft modifications. Unlike the transmitter, the receiving equipment is usually not limited in size or weight. An example shaft-mounted telemetry system for data transmission is shown in Figure 5. The shaft-mounted transmitter is battery powered (not RF-powered) and only transmits data.

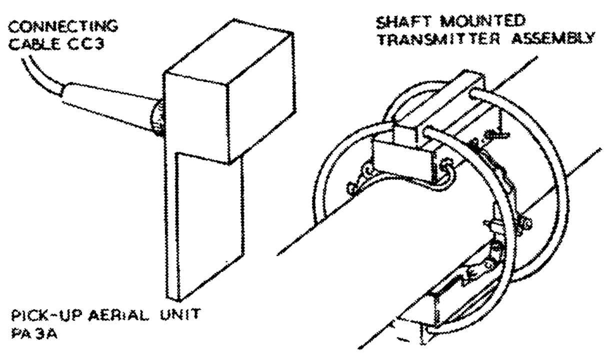


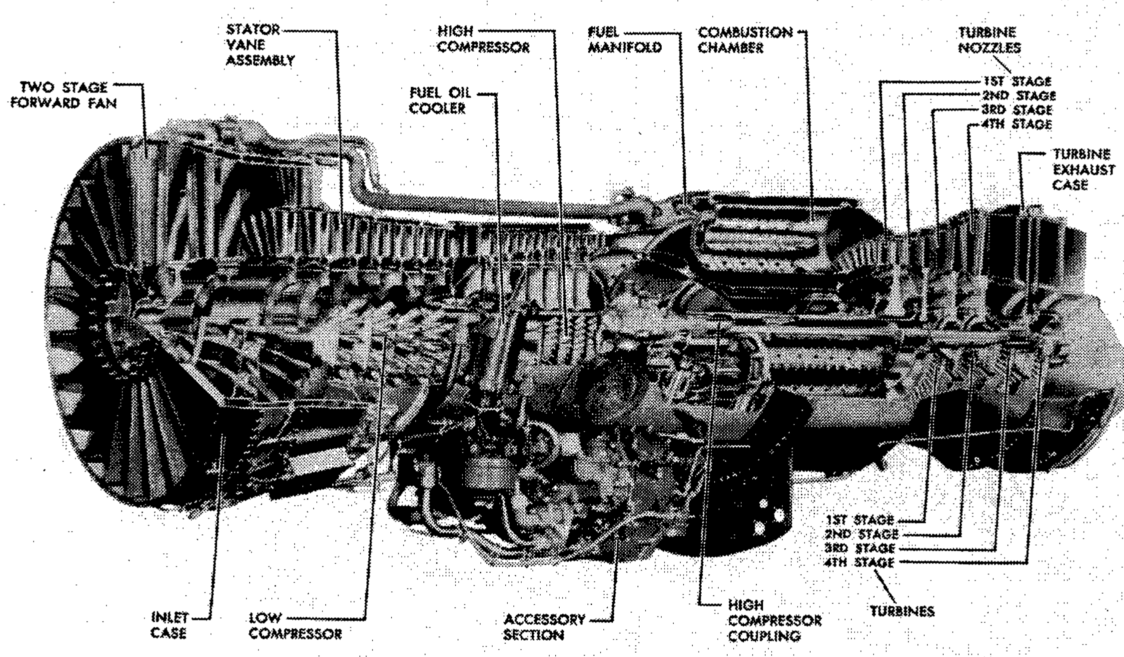
Figure 5: Example shaft-mounted, telemetry system for data transmission.

Campbell (1956) of the General Electric Co., compared results of radio-telemetered and slip-ring torque values and found the radio-telemetry system to be more accurate. Valentich (1977) also showed that more accurate data can be obtained using radio telemetry as opposed to slip rings. His AM/FM system used a 50 MHz carrier. A 2 kHz, amplified signal was applied to the input of a strain-gage torque bridge whose output is proportional to shaft torque. The amplified output was frequency modulated at 50 MHz, sent to an oscillator-transmitter, and received and demodulated. The transmitter used a built-in 12 V battery. Various commercial systems were subsequently developed, culminating in the short-range, telemetry system by Acurex Corp. Mountain View, California. Their radio-telemetry systems could transmit strain, temperature, current, voltage, resistance, and piezoelectric transducer signals. Like the earlier systems, the Acurex system used batteries to power the transmitting station. They also developed a system for long-term tests which uses an induction couple to provide power to the transmitting station. The Acurex system represented the state-of-the-art circa 1977. Since then Invocon Inc.[2] and MTS Systems[3] have developed telemetry systems. The Invocon systems are not inductively coupled and are not suited for shaft-mounted operation as in rotating machinery. MTS Systems is developing an embeddable, wireless, strain sensor with an off-chip antenna. The antenna is roughly 2 cm in diameter. It receives wireless power from a hand-held reader and transmits sensor data back to the reader. The system operates over an air gap of a few inches. The MTS Systems strain sensor would not be suitable for rotating machinery.

TELEMETRY CHALLENGES IN A GAS-TUBINE ENGINE ENVIRONMENT

To appreciate the complexity of the gas-turbine environment, a picture of an engine is given in Figure 6. A typical engine evaluation and certification test may use 3500 sensors. Routing the wire leads from the sensors through the engine for connection to the data-acquisition system requires vast resources in time and money: from six to nine months and several million dollars. Extensive rework of the engine hardware is also necessary before installing the sensors and interconnects. Besides the installation time and cost, wire interconnects between the sensors and data-acquisition system are unreliable, and time is wasted making continuity and resistance checks.

Telemetry systems for gas-turbine applications face severe challenges not associated with the common, long-range telemetry systems used in commercial and personal communications. The gas-turbine environment is characterized by high temperatures, high centripetal accelerations on rotating elements, and is often surrounded by highly-conductive metallic materials. To better understand the challenge, a typical gas-turbine environment will be described.



JT3D Nonafterburning Engine Cutaway

Figure 6: Typical turbine engine with labels on important components.

[2] Invocom Inc., Woodlands, Texas, www.invocon.com.
[3] MTS Systems, Eden Prairie, MN, www.mts.com.

1. High-Temperature Environment

The engine-case temperatures for a typical turbojet engine is shown in Figure 7[4]. The case temperature remains below 400 °F (204 °C) throughout the compressor region and rises to 1000 °F (538 °C) by the turbine inlet. The gas-path temperatures for a Pratt & Whitney JT9D turbofan engine are shown in Figure 8. Air temperatures reach 880 °F (471 °C) at the compressor exit and 1970 °F (1077 °C) by the turbine inlet.

To protect the telemetry package from these temperatures, it is usually placed in the engine bearing oil, which is cooled to below 257 °F (125 °C).

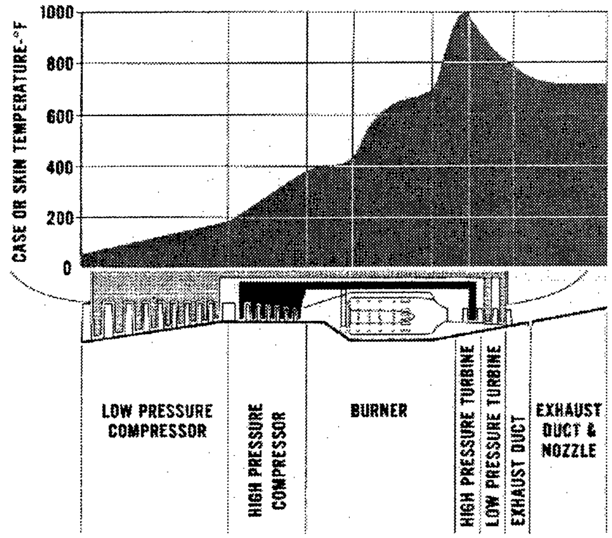


Figure 7: Typical outer-case temperatures for example turbojet engine.

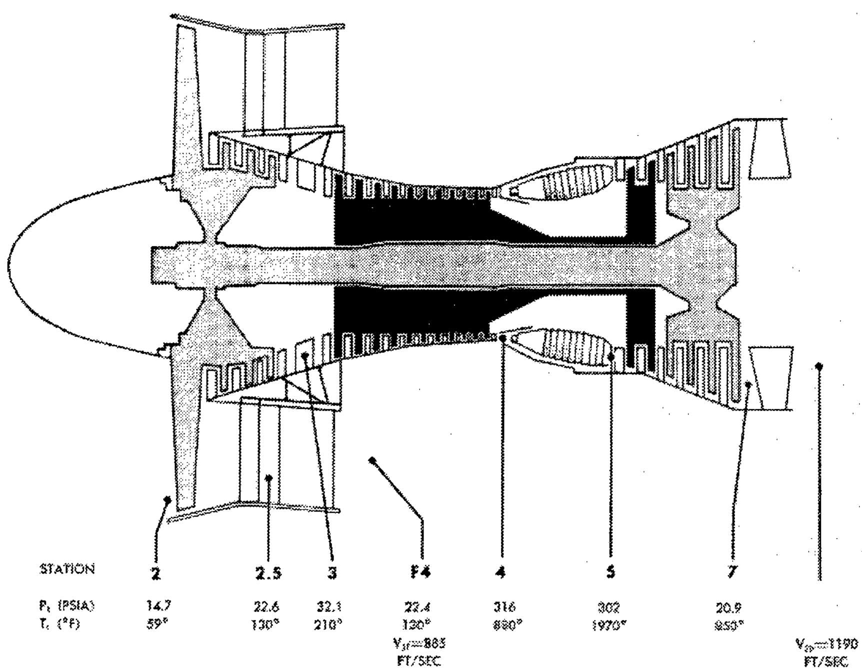


Figure 8: Pratt & Whitney JT9D turbofan internal air pressures and temperatures.

[4] Reference: The aircraft Gas Turbine Engine and its operation, Pratt & Whitney Aircraft, August 1970.

2. Centripetal Accelerations and Rotating Transmitters

Transducers and transmitters on rotating components may experience a centripetal acceleration up to 75,000 – 100,000 g. To complicate matters, this maximum acceleration often occurs simultaneously with the maximum temperature. Furthermore, transmitters translating around conducting objects suffer signal-strength variations and severe multi-path interference when operating through full 360° rotation in the presence of metallic material. Once-per-revolution transmission while passing by the receiving antenna is one potential solution for rotating transducers needing only periodic queries.

Rotating but non-translating transmitting antennae is the usual method for transmitting from rotating machinery. A short, straight wire antenna on the axis of the rotating part (shaft) is one method. This is possible only if the end of the shaft is accessible. A ring of wire (coil) completely surrounding the shaft is the usual configuration for the transmitting antenna. In either case, the receiving antenna may also be looped around the shaft. The size and shape of the transmitting antenna is usually restricted, but the receiving antenna may take many forms. Its length may vary from a few inches to hundreds of feet. In theory, the transmitting antenna may be of any length, but long wires tend to become charged when moving rapidly through air and may cause a spark discharge. In general, the distance between transmitting and receiving antennae should be as short as possible.

3. Metallic Environment and Skin Depth Effect

Metallic objects located between transmitter and receiver interfere with the transmitting signals and radio-frequency (RF) propagation becomes unpredictable. RF signals are not propagated through conducting metals, but instead are reflected from them. Depending on the transmitting frequency and material thickness, a metallic housing completely surrounding a radio transmitter may block or attenuate RF propagation[5]. Signal attenuation increases with increasing radio frequency and housing thickness according to the skin depth.

For metals or other good conductors[6], the depth of penetration (skin depth) of the RF field is defined by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}},$$

where f is the frequency of the field, μ is the permeability of the conductor, and σ is the conductivity of the conductor. For titanium, $\sigma = 23.8 kS/cm$, $\mu = 1.26 \mu H/m$ (Weast 1988), and δ is 0.59 mm at 0.3 MHz, 0.19 mm at 3 MHz, and 0.06 mm at 30 MHz. For every interval of δ along the metal thickness, the field strength attenuates to 1/e (≈0.37) of its original value. Most gas-turbine components are very effective RF shields because they are significantly thicker than the skin depth at practical RF frequencies. Thus it would not be possible to transmit RF signals from inside the engine casing to an outside data-acquisition system. One solution would be to use a short length of wire passing from inside the housing through a hole to the outside.

4. Gas-Turbine Typical Measurements

Typical measurements of interest in a gas turbine include dynamic pressure, steady-state pressure, dynamic strain, static strain, air temperature, surface temperature, vibration, and acceleration. Some of these measurements are necessary on both rotating and stationary components. The following specifications are from Viel et al. (1998).

Dynamic pressure measurements are desired on both rotating and stationary components. Rotating measurements with sensors on the airfoil to map dynamic pressure are desired. The frequency is 5-10 times the blade passing frequency at temperatures up to 1400 °F (760 °C). The rotating sensors could experience 100,000 g centripetal loading. Static-frame pressures to a minimum of 50 kHz (desired 500 kHz) in a range of increments to optimize sensitivity (0 - 50 psia, 50 - 100 psia, ... , 300 - 400 psia) are needed. Stationary

[5] This can be an advantage. Cardiac pacemakers use the electromagnetic shielding effects of a metal capsule, eliminating a major problem with electro-magnetic interference (EMI). In addition to the metal capsule housing the entire circuit, local shields can be used to isolate significant EMI sources or components particularly sensitive to EMI.

[6] Non-metallic materials such as ceramics would not shield RF signals.

pressure measurements in the combustor require 150-300 psia range in a 700 - 2800 °F (370 - 1540 °C) temperature environment. If cooling the transducers is necessary, cooling to 1400 °F (760 °C) is desired, but cooling to 900 °F (480 °C) is acceptable.

Steady-state pressure requirements include stationary measurements of static pressure on surfaces and gas-path total pressure. Static-pressure range is 15 - 80 psia on the fan to 15 - 400 psia on the compressor and turbine. Gas-path total pressure sensors are typically packaged in a rake to permit profile measurements across the flow path. No steady-state pressure measurements are needed on rotating components.

Dynamic strain measurements are desired up to 40 kHz at up to 1200 °F (650 °C) using strain gages or optical techniques with an uncertainty less than 10 -15%. Static strain has similar requirements between 0 and 5 Hz.

Air-temperature measurements to 1200 °F (650 °C) in the compressor and up to 3600 °F (2000 °C) in the exhaust are desired. No rotating air-temperature measurements are necessary. Currently, air temperature is measured using costly and intrusive thermocouples and rakes.

Surface temperatures include stationary measurements on all five major components--fan, compressor, combustor, turbine, exhaust--from below ambient in the fan to 2500 °F (1370 °C) in the exhaust at low-frequency; rotating surface temperatures include the fan, compressor, and turbine up to a temperature of 2200 °F (1200 °C) on the high-temperature turbine.

Dynamic acceleration measurements are needed on both stationary and rotating components. Rotating measurements are complicated by the 50,000 – 100,000 g centripetal accelerations. Since this acceleration is constant and always directed radially, the accelerometer must be properly oriented to be insensitive to this component. Dynamic accelerations typically encountered on machinery running at 10,000 – 60,000 rpm are usually up to 100 g. The frequencies are the first few multiples of the running speed, blade-pass frequencies, and gear-mesh frequencies, for gearing systems. For most machinery, a bandwidth of 1.5 Hz to 10 kHz catches all the normal vibrations. Stationary-component measurements would be similar without the background centripetal acceleration.

5. Telemetry System Specifications

Two independent telemetry scenarios are envisaged: a multi-channel, inductive-coupling for rotating measurements and a microsensor module for stationary measurements. Channel capacity for the multi-channel system should allow at least 100 dynamic-strain and 100 temperature measurements. Presumably, dynamic pressure measurements are also needed. Operating temperature range is 8 - 500 °F (–13 - 260 °C). The goal is to operate in an engine without need for special cooling. The environment may be hot air or hot engine oil. The maximum centripetal load is 60,000 to 75,000 g. The frequency response for dynamic strain is 10 Hz to 40 kHz and d.c. to 1 kHz for thermocouples. Pressure and vibration signals can require a bandwidth from d.c. to 10 kHz or up to 50 kHz for unsteady pressure.

The microsensor telemetry module size should be less than 2.5 cm length, by 1.25 cm width, by 0.625 cm height and weigh less than 10 to 15 grams. Power per module should be less than 1 watt, and the power source would be provided by inductive telemetry (100 kHz – 250 kHz preferred) or battery. Recommended transmitter type is PCM/FM. The operating life is greater than 1000 hours at maximum temperature and g. Eleven or more channels per module from d.c. to 50 Hz minimum or 1000 Hz preferred is needed. Typical inputs are type K and other thermocouples with d.c. millivolt levels. Range is –94 - 2500 °F (–70 - 1370 °C), which corresponds to –50 mv to +50 mv with type K thermocouples. Static strain requirements include two or more channels per module using a typical four-arm bridge of 350 ohms. Excitation is 5 or 10 Vdc. Frequency response is d.c. – 50 Hz, or d.c. – 1000 Hz preferred. A "stick on," non-intrusive, wireless microsensor module containing sensor, conditioning, computation, and communication circuitry is the ultimate goal.

As mentioned in the previous section, two telemetering scenarios are envisaged: a multi-channel, shaft-mounted, inductively-coupled system for rotating sensors; and a microsensor telemetry module for transmitting stationary or rotating sensor signals to a remote location on the stationary frame. Ideally, the microsensor module could eliminate wires and connections and transmit directly from the sensor location to a remote receiver. Because of multi-path interference, however, rotating (and some stationary) sensors may have to be hardwired to a remote transmitter before being telemetered to the data acquisition system.

A reasonable goal for these telemetry systems is operation at a temperature up to 500 °F (260 °C). This would allow an uncooled package located outside the gas path in the compressor region. The transmitting package would have to be cooled in the combustor and turbine sections. Designing a telemetry system for operation at 260 °C and beyond will be challenging.

Karnani (1998) demonstrated wireless telemetry using inductive coupling of power and data at 392 °F (200 °C), and makes recommendations on high-temperature components such as capacitors, resistors, oscillators, and solder. Ceramic and glass capacitors and Teflon-coated wires[7] were used. Solder (95 Pb-5 Sn) is available with melting temperatures up to 570 °F (300 °C). Gold-silicon (Au-Si) and gold-germanium (Au-Ge) solder are available with melting temperatures up to 715°F (380 °C). The variation of resistivity with temperature is the most important effect on resistors. Other problems with resistors include noise, thermal stress, interdiffusion, and oxidation. Karnani measured a 2.5 % frequency change between 71 °F and 482 °F (22 °C and 250 °C) using a conventional L-C oscillator operating at 66 MHz. A crystal-controlled oscillator operating at 49 MHz had only a 0.12 % change over the same temperature range. High-temperature electronics failures are often due to packaging technology rather than the actual material employed or the electrical failure of the component.

INDUCTIVELY-COUPLED TELEMETRY SYSTEM

1. Introduction

Only about sixty of the 3500 sensors used during a typical certification test are located on rotating components. These are transmitted to the stationary frame via inductive coupling from a shaft-mounted telemetry system. Hardware size limits the current system (telemetry or slip-ring systems) to approximately thirty channels. Hence, only half of the data from the rotating sensors can be obtained at one time. More rotating measurements would be made were the cost reduced and the hardware available.

Current telemetry systems use 1970's analog technology, require cooling below 257 °F (125 °C), and have limitations in accuracy and channel capacity. A new system should be digital and allow improved data quality and quantity, while allowing operation at higher temperature -- at least 392 °F (200 °C) -- in the hot gearbox oil where these systems are frequently located. The system would require shaft mounting. Since the telemetry system is rotating, sensors are usually hardwired to the telemetry system.

Usually, long-term tests cannot depend on battery power or other renewable power sources and must use telemetry for powering the sensor and transceiver. Transmitting significant power over large distances is highly inefficient; hence, inductive coupling is used. Even with inductive coupling, power cannot be transmitted very far. For example, Figure 9 shows how received power decreases with link distance from 0 to 4 cm (Tang, 1997).

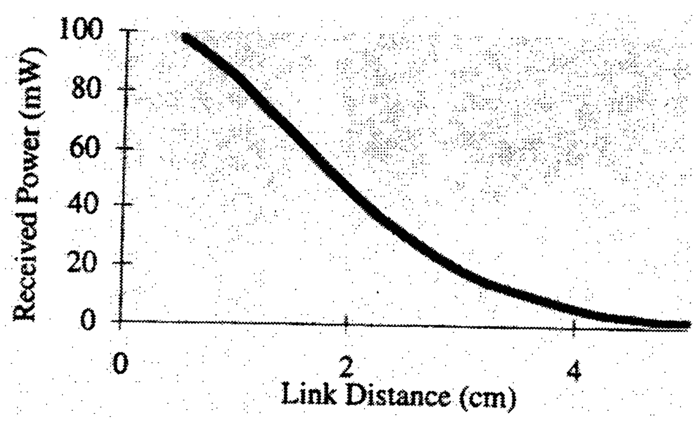


Figure 9: Received power versus coil separation in an inductively-coupled system.

[7] Teflon coated wires may be used up to 500 °F (260 °C).

This transmission technique is commonly referred to as "RF powering". By on-off modulating the RF-powering carrier, a communication system can be physically integrated into the RF-powering link to transmit binary data along with power. This method has been used to transmit binary data at 100 kb/s, with an average power transfer efficiency reduction of less than 10 % (Tang, 1997).

The RF-powering system should meet these four requirements: (1) maximization of coupling efficiency, (2) stabilization of voltage received by transmitter, (3) data transmission to transmitter, and (4) data transmission from transmitter. This type of system allows only small movement between transmitter and receiver, and voltage stabilization circuitry is necessary when relative movement between transmitting and receiving coils is significant. A powering system with bi-directional data transmission is the most flexible; a powering system with data transmission in one direction may be used in certain applications. Alternative powering techniques are given in the appendix.

2. RF-Link Description

As shown previously in Figure 3, in RF powering, two inductive antennae (coils) form the primary and secondary windings of an air-core transformer. For power transfer, the transmitting coil (primary winding) is wired to the data-acquisition system and the receiving coil (secondary winding) is wired to the sensor. The resulting electromagnetic couple is commonly referred to as a RF link, a RF couple, an inductive couple, a transformer couple, or a RF-inductive link. Throughout this paper, "RF powering" refers to the technique; "RF link" refers to the transformer couple consisting of the coils and the tuning elements.

"Critical coupling" is the desired technique for applications when the relative movement between coils is small and power consumption is low. The method utilizes the property of the resonant (double-tuned) transformer couple in that there is an operating point at which the voltage gain as a function of coupling coefficient is the maximum and most stable. The theoretical power transfer efficiency is 50%. A basic circuit model for a transformer couple (RF link) is shown in Figure 10.

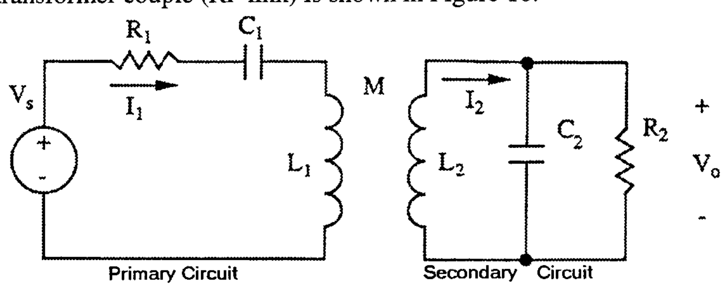


Figure 10: Basic circuit model for a RF induction link.

The primary circuit transmits RF power to the secondary circuit which contains the sensor. In the primary circuit, an a.c. power source supplies the current in the primary coil creating the electromagnetic field. The field lines are coupled to the secondary circuit through the secondary coil. Hence, power is transmitted from the primary to the secondary circuit. The data from secondary to primary is also transmitted through the same RF link. The coil and capacitor in the secondary circuit form a resonant tank circuit in which the electrical oscillations occur at a specific frequency of constant amplitude. The charge of electrons moving back and forth between the plates of the capacitor creates a magnetic field in the secondary coil. Energy is radiated by this coil in the form of radiowaves, and the magnetic field that surrounds the coil generates alternating currents in the nearby conductors. In particular, the magnetic field generates a signal in the primary coil. The performance of the transmitter can be altered by changing the resonant frequency of the tank circuit. The resonant frequency can be increased by using a lower value capacitor or by winding a coil with fewer turns. The same argument applies to the primary circuit and resonance occurs when the primary circuit is tuned to the frequency of the generator.

Proper tuning eliminates reactive power loss and therefore maximizes the efficiency as defined by the ratio of the power dissipated in the resistive load to the power delivered from the power source. The primary and secondary circuits must resonate at the same frequency. Adjusting capacitors C_1 and C_2 is a typical way of tuning the circuit. L_1 and L_2 represent the inductances of the coils. When the primary and secondary circuits resonate, the amplitudes of the impedances Z_1 and Z_2 are minimum (due to the zero reactance). The current is in phase with the line voltage at resonance, the inductive reactance X_L is equal to the capacitive reactance X_C, and the resonant frequency is

$$f_R = \frac{1}{2\pi\sqrt{LC}}.$$

The sharpness of the resonance is determined by the Q factor defined as

$$Q = X_L/R = 2\pi f L/R.$$

High-Q circuits are desired to maximize power transfer. In wide-temperature applications, however, high-Q circuits are not the only goal because LRC components have temperature-dependent properties and the circuit can drift out of resonance if the circuit Q is too high. Hence, the circuit gain should be spread out over a larger band of frequencies in order to accommodate any frequency variation. Q equal to 23 was used by Karnani (1998) in a circuit designed to operate over a temperature range of 392 °F (200 °C). The low Q was obtained by using a transmitter coil with only two turns of copper[8].

A critical issue for gas-turbine applications is the proximity of the coils to magnetic materials like steel. Valentich (1977) measured reduced power transfer and tuning anomalies with coils near magnetic materials. He measured a linear increasing voltage in the secondary circuit from 52 V to 79 V when the secondary coil was moved away from the shaft from 1.25 cm to 7.5 cm. He also found that the maximum voltage measured in the primary circuit was cut in half and the Q reduced when a steel plate was placed near the shaft-mounted primary coil. It must be emphasized that steel in close proximity to a primary or secondary coil will act as a third coil and absorb energy from the primary coil. The system must therefore be designed so that the power coils are located as far as possible from steel, or else sufficient excess power must be available at the primary coil so that the losses can be tolerated. A ferrite core may be used in the secondary coil to improve efficiency. When using ferrite, however, the frequency dependence of the permeability must be observed to avoid possible saturation at high frequencies.

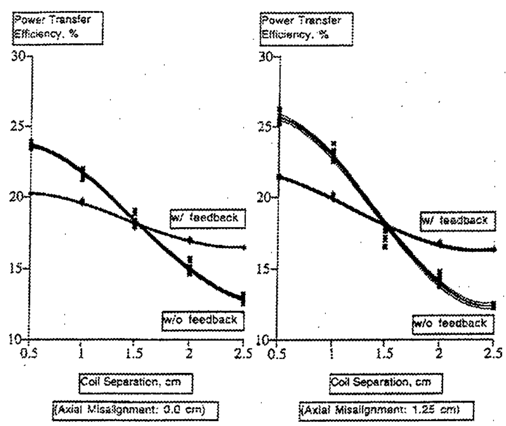


Figure 11: Power-transfer efficiency versus coil spacing for 7 MHz system.

As discussed previously, the spacing between coils and the diameter of each coil should also be designed to maximize power transfer. Figure 11 shows how rapidly power-transfer efficiency drops as the distance between transmitting and receiving coils increases from 0.5 to 2.5 cm. This system operated at 7 MHz and delivered 150 mW at 33 V (Tang, 1997). Feedback does improve efficiency, but the allowable separation is still only a few centimeters. Figure 12 shows how the received power varies with transmitter-coil diameter. See Ko et al. 1977, for design rules.

[8] Q is a function of inductance and inductance varies as the square of the number of turns of the coil.

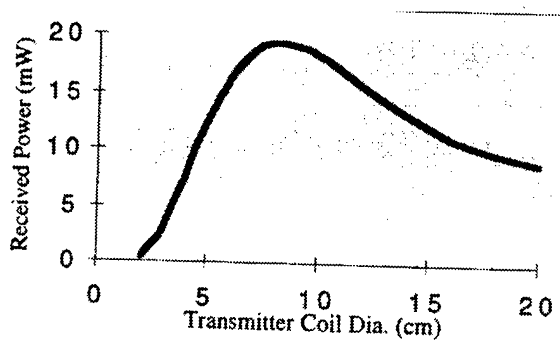


Figure 12: Received power versus coil diameter for 7 MHz system.

Inductive-coupling examples from the medical field are illuminating. Since it is desirable for implantable devices to have no batteries, inductive powering and wireless data transmission are used. These systems operate in the millimeter-wave frequency range. Glasser et al., (1989) used an air-core coil to transmit 0.9 mW over distances of a few millimeters. This coil had low inductance and a very low Q. Von Arx and Najafi (1997) built coils with integrated NiFe cores and achieved high inductance and Q and were able to transmit tens of milliwatts over distances up to a few centimeters. They used an 8 cm diameter transmitter coil. Their silcon-microfabricated, ten-turn receiver coil occupied an area of 2 mm by 10 mm, operated at 4 MHz, had a Q of 6.6, and supplied loads of a few kΩ with 15 mW of d.c. power over a distance of 3 cm. Screening due to the silicon substrate and degradation of Q due to parasitic substrate capacitance were not a problem at this frequency. The diameter of the transmitting coil was chosen to maximize the power received at the target implant depth. A larger transmitter coil results in deeper penetration of the field lines and tolerates more misalignment (maximum coupling occurs when the center of the smaller coil is misaligned by half the radius of the larger coil). However, larger-diameter transmitter coils also result in lower coupling coefficients.

3. Data Transmission

Data transmission (as opposed to the transmission of power) from the secondary circuit to the primary circuit may be done using load-shift keying (LSK) and a circuit configuration modulator (CCM) (Tang, 1995). The coupling between primary and secondary coils allows the secondary impedance to be reflected in the primary coil as Z_r. When the coupling coefficient is sufficiently large, Z_r becomes a significant portion of the impedance of the primary coil. A binary signal can be transmitted by modulating the secondary load and tracking the reflected impedance on the primary coil, a scheme referred to as load-shift keying. To effectively modulate the secondary load without sacrificing the power efficiency of the secondary circuit, a switch is used such that the ac-to-dc conversion circuitry is a bridge rectifier when it is open, and a voltage clamp when it is closed. The voltage clamp and bridge rectifier provide considerably different loadings, R_2 and R_2', on the secondary coil and significant changes in Z_r. This modulation circuit is referred to as circuit configuration modulator. When the coupling coefficient, defined as $k = M/\sqrt{L_1 L_2}$, (where M is the mutual inductance between the two coils) satisfies $k^2 >> R_1 C_1 / R_2 C_2$, neither the power efficiency nor the voltage transfer function of the RF powering system is dependent on the secondary load R_2. Therefore, it is possible to incorporate data transmission with LSK-CCM into the RF-powering system without affecting its original power efficiency and voltage transfer function.

It is impossible to track Z_r directly because it is a part of the impedance of the primary coil and cannot be physically isolated. However, the telemetered data can be monitored by tracking the primary current, I_1, which varies with Z_r, when V_s is a known voltage (Tang, 1997).

To satisfy the condition $k^2 >> R_1 C_1 / R_2 C_2$, R_1 is to be minimized and R_2 maximized. R_2 represents the fixed load. This corresponds to maximizing the Q of both the primary and secondary circuits, which results in minimum RF-link bandwidth. The minimum system bandwidth can be as narrow as $1/T$, where T is the duration of one bit. In practice, a bandwidth of $3/T$ is desired for reliable data detection (Stremler, 1982). In other words, the bandwidth should be three times the data rate. To maximize power efficiency, the data rate should be kept low, as long as it still allows sufficient time to accomplish communication tasks. A compromise between data transmission quality and power transfer efficiency is inevitable.

MICROSENSOR TELEMETRY MODULE

The microsensor telemetry module would incorporate microfabricated wireless components and sensors to achieve a miniature sensor-transmitter module. The module would acquire, process, and telemeter the sensor signal to a remote receiver located with the data-acquisition system. The system would be used for non-rotating measurements, since, as previously discussed, it would be difficult to receive a signal from a transmitter rotating inside an engine. The microsensor telemetry module would need on-board power from a battery or other source. As shown earlier, RF-powering fails beyond distances more than a few centimeters. Technology developed by the telecommunications and automotive industries could form the basis for a high-temperature telemetry system. However, alternative materials for high-temperature electronics are necessary. The silicon-based microsystems are limited to approximately 125 °C. Silicon carbide has the capability to operate up to 500 °C. Silicon nitride and diamond are also high-temperature materials.

Battery-powered transmitters are available for short-term testing or when sensor power consumption is low. Battery-powered transmitters are more flexible than a RF-powered devices since they do not need to be located close to the powering station. For example, a 2.4 V lithium battery is being used to power a wireless transceiver system for a micromachined, capacitive pressure sensor implanted in the air-valve stem of a tire.[9] The capacitive sensor, instead of the usual piezoresistive bridge sensor, keeps power consumption low and eliminates the need for a bias current. Total sensor current consumption is 4 μA at less than 2.4 V over a temperature range of –40 – 212 °F (-40 - 100 °C). The transmitter operates at 433 MHz and the receiver can be located in the vehicle's dashboard. This example shows that when power is not transmitted, low-power, wireless telemetry can be used to transmit data over several meters.

1. Background and Motivation

Narrow bandwidths for cellular and cordless phones require selective filtering devices for channel selection and stability. These can only be achieved using high-Q, discrete components because conventional IC technologies cannot achieve the required Q. High-Q is desired, because the most important parameter dictating oscillator stability is the Q of the frequency-setting tank. Noise spikes and temperature fluctuations affect stability and create phase shifts. The phase shift causes an operating frequency shift which depends on the Q of the resonator tank. Tank Q also greatly influences the ability to implement selective IF and RF filters with small bandwidth, shape factor, and insertion loss. Figure 13 shows example Bode plots for low-Q and a high-Q tank circuits and corresponding frequency changes for a phase shift of 40°.

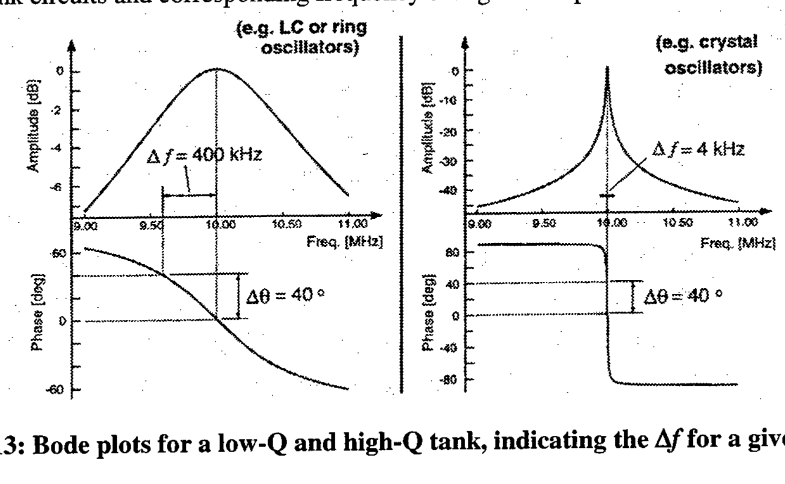


Figure 13: Bode plots for a low-Q and high-Q tank, indicating the Δf for a given Δθ.

[9] Swiss Center for Electronics and Microtechnology (CSEM), Electronic Design magazine, December 16, 1996, p. 40.

The majority of communications transceivers use high-Q, SAW and bulk-acoustic, mechanical resonators to achieve good frequency selection in their filtering stages and to realize low phase noise and stability in their local oscillators. Dielectric resonators or waveguide components are also required at RF or microwave/millimeter-wave frequencies to provide the high-Q functions. Discrete inductors and tunable capacitors are also used to tune and couple the circuit to the transmitter. At present, these discrete elements are off-chip components, which must interface with the integrated electronics. This can be expensive and unreliable, consume excess area, and preclude miniaturization of the complete transceiver. Microfabricated, integrated high-Q inductors, tunable capacitors, filters, switches, resonators, and antennae are emerging as replacements for off-chip equivalents. RF filters with center frequencies between 800 MHz and 2.5 GHz, IF filters with center frequencies between 455 kHz and 254 MHz, oscillators, and switches are also candidates for replacement with micromachined, mechanical equivalents. For higher-frequency applications past X-band, the antenna size shrinks, so the antenna itself can be microfabricated. Each of these elements will be discussed in the following sections.

2. Microfabricated Capacitors and Inductors

Voltage-controlled oscillators (VCO) are being developed using micromachined components. Currently, VCO's are implemented using off-chip inductors and varactor diode capacitors with Q's of at least 30. Young and Boser (1996) demonstrated a voltage-tunable capacitor composed of a micromachined, movable, metal plate (Figure 14). This capacitor could be tuned over a range of 16 % using 5.5 V range of bias with nominal capacitance of 2.2 pF. It is 200 μm by 200 μm in area. Four of these wired in parallel achieved a Q of 62 at 1 GHz.

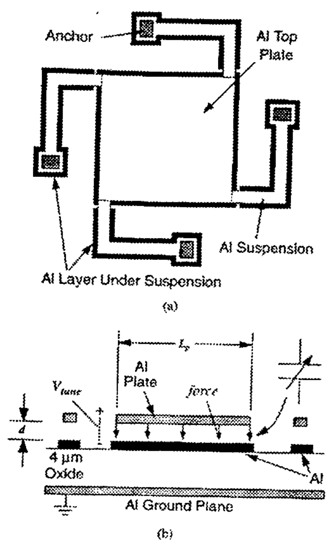


Figure 14: (a) Overhead and (b) cross-sectional schematics of a voltage-tunable microfabricated capacitor, Young and Boser (1996).

To achieve resonator tanks with adequate Q, high-Q inductors are also needed. Numerous attempts to implement spiral inductors using conventional IC technologies have not yielded sufficient Q. Current research is focused on more exotic micromachining techniques. Strategies include the use of magnetic cores to raise coupling in inductive coils and the removal of leakage to the substrate by fabricating inductors on suspended membranes. Von Arx and Najafi (1997) utilized an NiFe core under a planar metal spiral to achieve an inductance of 2.7 μH using ten turns in an area of 2 mm by 10 mm with a Q of 6.6 at 4 MHz (Figure 15). The coils suffer from self-resonance problems that limit their frequency range. Above self resonance, the permeability of the magnetic core drops. These inductors are still inadequate for some applications.

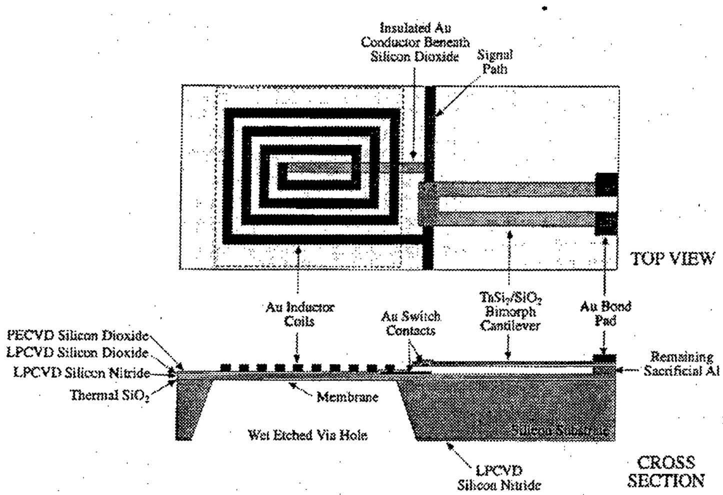


Figure 15: Microfabricated inductor top view and cross section, Von Arx and Najafi (1997).

3. Microfabricated Resonators

Q's on the order of 40 may be achieved with tunable capacitors and on-chip inductors. However, these elements will unlikely achieve the much higher Q's needed (in the thousands) to replace the vibrating mechanical resonators (e.g., quartz crystals) used in the more demanding reference-oscillator and channel-select filter functions. Initial research focused on thin-film technologies to yield miniature versions of vibrating mechanical resonators. These deposited piezoelectric films were sandwiched between conductors, and similar to quartz crystals, built on a suspended membrane for acoustic isolation from the substrate as shown in Figure 16 (a) (Krishnaswamy et al., 1991). Q's of 1000 and resonance frequencies of 1.5-7.5 GHz in sizes of 400 μm by 400 μm were demonstrated, but problems with structural integrity of the supporting membrane remain. The membrane was eliminated by Lakin et al. (1995) by isolating the piezoelectric resonator from the substrate using impedance matching (Figure 16(b)). Despite the progress, thin-film bulk-acoustic resonators still have problems with trimming and tuning these resonators is not yet possible.

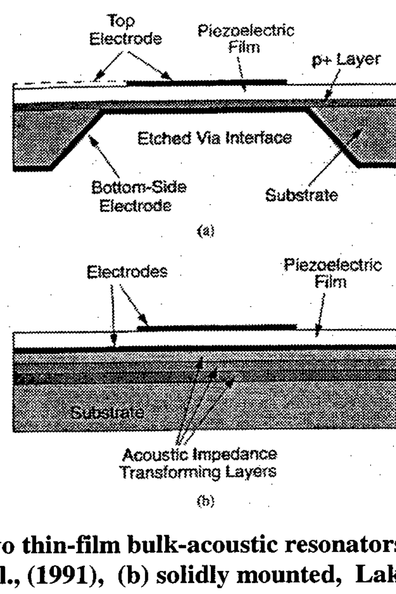


Figure 16: Cross sections of two thin-film bulk-acoustic resonators, (a) membrane supported, Krishnaswamy et al., (1991), (b) solidly mounted, Lakin et al., (1995).

Micromachined resonators with Q's on the order of 20,000 have been achieved at 70 MHz in single-crystal silicon (Nguyen and Howe, 1992) and Q's of 80,000 at low frequency have been achieved in polysilicon (Cleland and Roukes, 1996). In addition to their high-Q values and wide frequency range, mircomachined resonators have other attractive features: voltage-controlled frequency tunability and switchability, trimming capability, flexibility in geometry and structural materials, and flexibility in transduction method (electrostatic, piezoelectric, magnetostrictive). Fabrication is also simple and usually defined by a single masking step. The disadvantage is the need for vacuum sealing to obtain high Q, and an unaided temperature coefficient of resonant frequency of –10 ppm/°C (DeAnna et al., 1999), which is not as good as quartz. A typical folded-beam, comb-drive, lateral resonator and equivalent RLC circuit is shown in Figure 17 (Nguyen 1992).

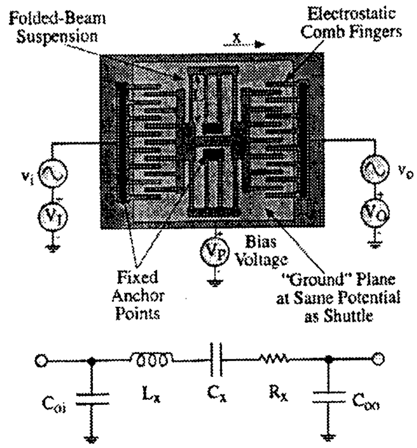


Figure 17: Microfabricated folded-beam lateral comb-drive resonator with equivalent RLC circuit, Nguyen (1995).

4. Microfabricated Waveguides

Another application of micromachining is the fabrication of three-dimensional cavities to synthesize miniature waveguide components at 10-60 GHz. A reduced-height resonant waveguide (with dimensions of $\lambda/2$) can be etched in a silicon wafer and fed either by a slot transition or by bond wires. These structures have yielded Q's of 500 at 10 GHz (Papapolymerou et al., 1997). An advantage of micromachined lines is the micropackaging aspect of this technique. A filter–or any component inside the microcavity–is completely shielded and therefore will not couple any RF energy to the outside world. Typical measured isolation between adjacent transmission lines is –50 dB at 30 GHz (Drayton et al., 1996).

5. Microfabricated Mechanical Switches

In addition to the filter and oscillator research, micromechanical switches for antenna or filter-path selection and for phased-array antennas are planned. So far, the majority of switches for communications have used electrostatic actuation. These switches normally outperform PIN diodes or GaAs field-effect transistors (FET's) in "on-state" insertion loss and "off-state" isolation. They also consume zero power when activated, unlike their solid-state counterparts, which sink a finite amount of current when activated. However, most are much slower than PIN or FET diode switches (4-20 μs versus 1-40 ns), and they require high actuation voltages (20 - 60 V versus 3 - 5 V). Micromachined switches are also prone to stiction problems in a metal-to-metal switch. However, micromechanical switches are attractive because of they are extremely linear devices. An example capacitively coupled, electrostatically actuated membrane-type RF switch is shown in Figure 18 (Goldsmith, et al. 1996).

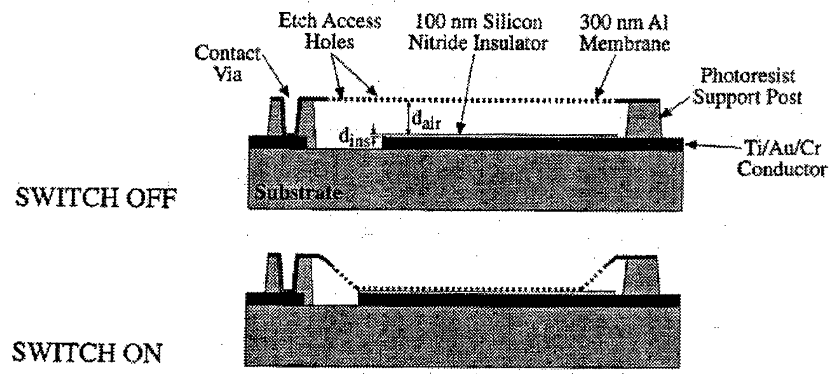


Figure 18: Capacitive-coupled, electrostatic-actuated, membrane-type RF switch Goldsmith et al., (1996).

6. Microfabricated Antennae

Micromachined antennae were first used at millimeter-wave and terahertz frequencies to reduce loss and size constraints at such high frequencies. However, antennae on Si/GaAs and quartz dielectrics are inefficient radiators at millimeter-wave and terahertz frequencies due to the electrical thickness of the underlying substrate. And standard CMOS technology cannot be used because of the lossy nature of the silicon substrate at microwave and millimeter-wave frequencies. (Currents induced in the silicon substrate due to electromagnetic coupling result in unwanted frequency dependent losses, making it very difficult to obtain high-Q resonant components and circuits.) At the same time, a large parasitic capacitance to the substrate generally limits inductor performance to below 1 GHz, unless multilevel processes are utilized to fabricate the circuits, which gives improved performance (Burghartz et al., 1996). Micromachining has therefore been used to remove the silicon substrate directly beneath, and in the vicinity of, the high-frequency elements to reduce the loss and parasitic capacitance. At millimeter-wave frequencies, techniques include suspended dipole or slot radiators on thin dielectric membranes, with the planar antennas effectively radiating in free space. Anisotropic etching has also been used to create pyramidal cavities in silicon to act as miniature horns around the dipole antenna, directing the radiated energy efficiently in the forward direction (Ali-Ahmad and Rebeiz, 1993).

For gigahertz frequencies, membrane technology results in large antennas and is not practical. Therefore, at these frequencies, membrane approaches are avoided, and micromachining is used to synthesize artificial dielectric-constant substrate materials underneath the antenna. By etching a portion of the dielectric or by strategically choosing the density of via holes underneath an antenna, a dielectric constant between one (complete removal) and ε_r (no removal) can be achieved. The efficiency of microstrip antennas at 12-13 GHz has been increased from 55 % (ε_r=10) to 85 % (ε_{synth}=2.3) (Papapolymerou et al., 1998). Similar techniques have been used at 77 GHz for automotive radar applications (Stotz et al, 1996). Alternatively, suspended transmission lines, inductors, capacitors, and filters can be used at microwave frequencies. Absence of the lossy silicon substrate after micromachining results in significantly improved attenuation and dispersion characteristics, Q's, and operable frequency range. The result are lumped elements and circuits operable up to 40 GHz with Q's up to 20 (Milanovic et al., 1997).

7. Conclusion

The need for higher Q values beyond the capabilities of conventional IC technologies have led to board-level passive components which occupy a substantial portion of the overall area in transceivers and present a bottleneck to further miniaturization. Micromechanical resonators and passive components offer an alternative strategy. These micromachined elements will be required components in a microsensor telemetry module. Thus, it is important to be aware of developments in this area. Nguyen et al. (1998) offer more information and details of micromachined devices for wireless communications.

SUMMARY AND CONCLUSIONS

Gas-turbine engine evaluation and certification tests may require up to 3500 sensors. Routing wire leads from the sensors through the engine for connection to the data-acquisition system is both costly and time consuming. Extensive rework of the engine hardware is also necessary to route these wires. And wire interconnects between the sensors and data-acquisition system are unreliable and require continuity and resistance checks. Many of these problems could be eliminated with a microsensor telemetry module. This module would be co-located with a sensor and would transmit sensor signals using RF-telemetry. This technique would be limited to those sensors on the static frame and would likely fail for rotating sensors because of reflections of the wireless signal by metallic components. However, if continuous data transmission around the full 360° rotation were not necessary, once-per-revolution data could be sent from a rotating microsystem telemetry module as it passes a fixed receiver located on the static frame. Even RF-telemetry transmission in the static frame is challenging because of the 'skin effect' which prevents electromagnetic waves from penetrating the surface of conductive materials and causes them to propagate along the surface.

This microsystem module will have to survive in the high temperature (500 °C at the compressor exit), harsh environment of the gas turbine. Corrosive gases and possible centripetal loads up to 100,000 g increase the challenge. The micro-wireless components and systems under development for communications applications could form the basis for this module, but alternatives to silicon must be used for the high-temperature electronics. One of the biggest challenges is providing power to the module. High-temperature batteries are one solution. Transmitting power to the microsystem module using wireless telemetry techniques is not possible if the distance is more than a few centimeters.

Another wireless-telemetry system completely independent of the microsystem wireless module would use inductive coupling between transmitter and receiver and allow both data and power to be sent wireless. This system would be used to transmit power and data between the rotating and static frames. The rotating piece would be mounted on the end of the shaft and separated from the stationary piece by a fraction of a centimeter. This system would be an advanced version of the system developed by Acurex Corporation in the 1960s. Higher-temperature capability is needed along with more channels and better signal-to-noise ratios. Wire leads would still be required between the shaft-mounted telemetry package and the sensor locations.

Because of the problems caused by the 'skin effect' and the rotating reference frame, a possible compromise system could use wire leads between sensors located in the 'heart' of the engine and telemetry modules located on the outside of the engine casing. These battery-powered modules could provide power to the sensors and transmit a wireless, sensor signal to the data-acquisition system. Although of limited appeal and far from the goal of an integrated, sensor-wireless module, this system may be a useful first step.

APPENDIX: ALTERNATIVE POWER SOURCES

There are several alternatives to RF-powered telemetry systems for power transmission. These alternatives deserve a thorough study of their own and are only included for reference.

1. High-Temperature Batteries

Typical batteries for portable equipment are rated to 185 °F (85 °C). Lithium batteries are rated up to 350 °F (177 °C). And there are advanced batteries available for operation up to 570 °F (300 °C), but they cost $2000 each.

2. Thermal Photovoltaic (TPV) Power Sources

One innovative power source under active investigation by NASA Glenn Research Center uses thermal photovoltaics (TPV).[10] This system captures the radiant energy of a flame in the IR-frequency range. The photovoltaic materials are semiconductors with small band gaps in the 0.5 to 0.8 eV range and operate at surface temperatures typically around 2370 °F (1300 °C). Researchers at McDonnell-Douglas demonstrated a SiC emitter and a 0.69eV cell. This combination produced 1.9 W/cm^2 of electrical power with an efficiency of 27 % and a 1400 °C emitter temperature (Wilt and Chubb, 1998). Although the optimal surface temperature is significantly lower than the combustor wall temperature, it is conceivable the technology could be used with cooling air to power sensors in the hot section of a gas-turbine engine.

3. Thermionic Diode

This device converts heat into electrical power. This technology is being used as a solar thermal propulsion demonstration for space applications.[11]

[10] Contact David M. Wilt of the NASA Glenn Photovoltaics Branch, ph. (216) 433-6293. Also reference 4th Thermophotovoltaic Generation of Electricity conf (AIP conf. proc. 460), Denver CO, 1998.
[11] Philips Laboratory Space and Missiles Technology Directorate, Air Force Material Command, Kirtland Air Force Base, NM 87117-5776, report PL-TR-96-1006.

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13. ABSTRACT ***(Maximum 200 words)***

Wireless telemetry technology for transmitting power and data to and from sensors located inside a gas-turbine engine is reviewed. Two scenarios are considered: a rotating sensor hardwired to a shaft-mounted, inductively-coupled system; and a stationary or rotating microsensor telemetry module. Applications of these telemetry scenarios in the gas-turbine operating environment, the types of sensor measurements, the principles of telemetry, and a review of the current state of microfabricated components for telemetry systems are given. Inductive coupling for both data and power transmission is emphasized in the first scenario. The microsensor telemetry module discussed in the second scenario would need battery power or an alternative power source. These technologies are emerging and do not represent available products. A brief list of alternative technologies for providing power is presented at the end.

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