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Abstract

Aircraft engines have evolved into a highly complex system to meet ever-increasing demands. The evolution of engine technologies has primarily been driven by fuel efficiency, reliability, as well as engine noise concerns. One of the sources of engine noise is pressure fluctuations that are induced on the stator vanes. These local pressure fluctuations, once produced, propagate and coalesce with the pressure waves originating elsewhere on the stator to form a spinning pressure pattern. Depending on the duct geometry, air flow, and frequency of fluctuations, these spinning pressure patterns are self-sustaining and result in noise which eventually radiate to the far-field from engine. To investigate the nature of vane pressure fluctuations and the resulting engine noise, unsteady pressure signatures from an array of embedded acoustic sensors are recorded as a part of vane noise source diagnostics. Output time signatures from these sensors are routed to a control and data processing station adding complexity to the system and cable loss to the measured signal. "Smart" wireless sensors have data processing capability at the sensor locations which further increases the potential of wireless sensors. Smart sensors can process measured data locally and transmit only the important information through wireless communication. The aim of this wireless noise telemetry task was to demonstrate a single acoustic sensor wireless link for unsteady pressure measurement, and thus, establish the feasibility of distributed smart sensors scheme for aircraft engine vane surface unsteady pressure data transmission and characterization.

Introduction

Wherever an array of sensors is implemented, wireless communication appears more appealing. Wireless sensors convert analog signals to digital streams prior to RF transmission, while wired systems route analog signals to a processing station for signal conversion. So, digital conversion at the wireless sensor node eliminates possible signal degradation during analog signal transmission through long cables. A wireless sensor system promises reliable data acquisition and transmission for a large number of sensors embedded on large structures.

A smart sensor or mote is inherently different than a traditional sensor as defined by three characteristic features: onboard computational ability by means of a microprocessor, the ability to store sensed data prior to processing and store process instructions and numerical algorithms in onboard memory, thus, acts truly wireless both from data-acquisition and from power supply perspective. The wireless feature of a smart sensor requires that the node is either self-powered or battery powered and has an onboard radio to transfer processed data to another access node point.

Smart sensors, however, have some limitations. Depending on application, sensor sampling speed may be too slow, clocks on different sensor nodes may not always be synchronized, as well as limited memory storage capacity and slower than PC processor speed often are the major drawbacks. Moreover, battery power imposes limitations on many aspects of smart sensors. Any task consuming large amounts of power becomes impractical on a battery-operated smart sensor node. Any system employing smart sensors needs to overcome these limitations through deliberate system design (Table 1).

TABLE 1.—INTEL IMOTE2 RADIO FEATURES

Features	Value
Processor, variable speed	(PXA27x)
Clock speed	13 to 416 MHz
Active power (mW)	44 at 13 MHz, 570 at 416 MHz
Radio	ChipCon 2420 802.15.4
Flash memory	32 M
RAM (bytes)	256 K + 32 M external
Non-volatile storage	32 M
Size	48 × 36 × 7 mm

Intel's Imote2 smart sensor platform does not provide the sensing capability but comes with a few available sensor interface boards, digital I/O ports, a low power processor and 802.15.4 radio with a built-in 2.4 GHz antenna for processing data intensive applications (Fig. 1). Other wireless sensor platforms, such as the MicaZ, or TelosB Motes have focused on ultra low power performance and low data-rates. Although Imote2 is well suited to high bit-rate applications, it does not come with ultrasonic signal sensing interface boards. To integrate a microphone sensor with a commercial Imote2 platform requires a custom-developed *sensor interface board* (Ref. 1).

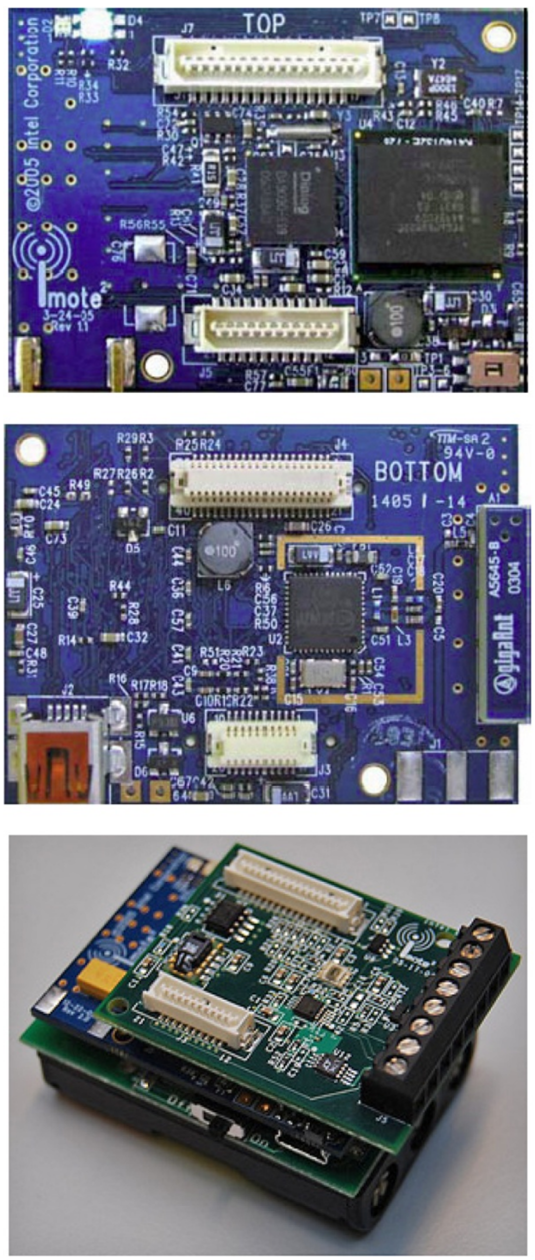

Figure 1.—Top, bottom, and vertically stacked view of Imote2 smart sensor platform.

Engine Noise Telemetry Concept Development

This section briefly covers engine fan noise source diagnostics problem, the rationale behind "wireless" telemetry of noise data, then reviews Intel's Imote2 wireless radio platform and its *Basic Sensor Board* and highlights the motivation behind developing a flexible sensor board to specifically address the measurement needs in Subsonic Fixed Wing (SFW) fan noise reduction problem. The design concept of a SFW acoustic sensor board to interface with the Imote2 wireless radio module is presented subsequently. SFW acoustic sensor board was designed to meet the bandwidth requirement imposed during wind tunnel measurement of noise level from 1/5th to 1/10th scale model test engines. Bandwidth requirement for measurement of acoustic noise signals from 1/5th to 1/10th scale model test engines is inversely proportional to their engine scale model factors. Thus, to simulate test data covering audible noise signal bandwidth of 2 to 20 kHz from a full scale engine, a 1/5th scale model test engine signal bandwidth has to range from 10 to 100 kHz, thus requiring a Nyquist frequency of over 200 kHz setting analog to digital (ADC) signal sampling rate at less than every 5 µsec.

Engine Vane Noise Source Measurement Problem Statement

To meet stringent aircraft noise reduction standards in pursuit of quieter aircraft engines for civil aviation, a comprehensive wind tunnel test called engine noise Source Diagnostics Test (SDT) was conducted at GRC in order to understand the basic noise generation mechanism and, specifically, the sources of noise within a turbofan engine (Ref. 2) (Fig. 2). As part of noise source diagnostic test, pressure fluctuation time histories from vane embedded microphones at discrete locations inside a stator vane for various flow conditions was measured inside GRC wind tunnel.

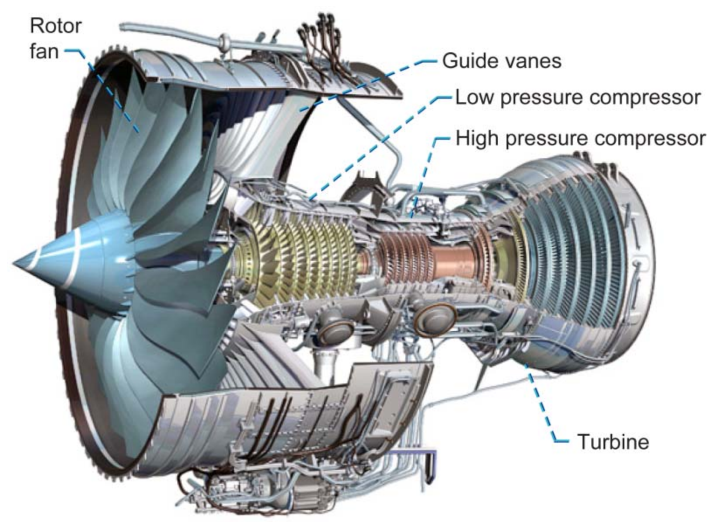

Figure 2.—A turbofan engine cutaway view.

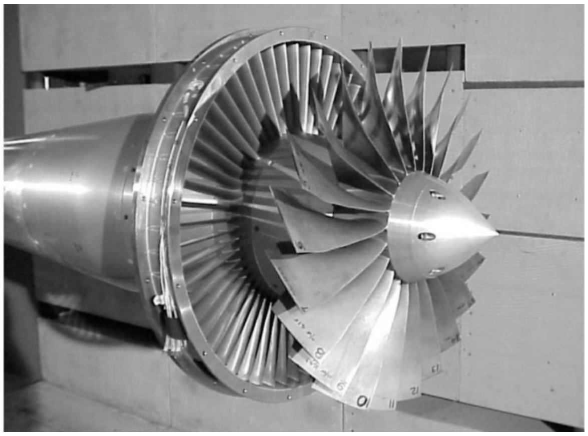

Figure 3.—Engine outlet guide vane (stator) and fan (rotor) blades in perspective view.

Figure 4.—An engine under test in GRC wind tunnel.

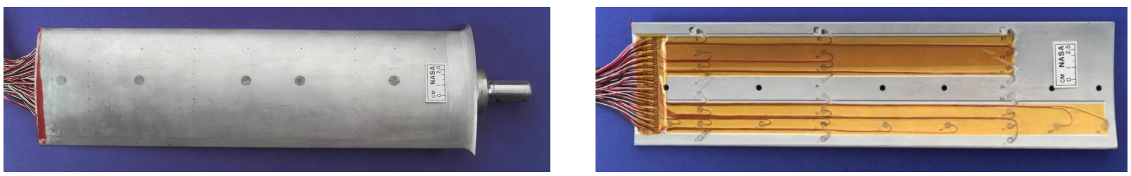

Figure 5.—A stator vane with embedded pressure transducers.

Engine rotor-stator interaction noise is primarily generated by the pressure fluctuations that are induced on the stator vanes due to the impingement of high speed air forced by the rotor fan. These local pressure fluctuations, once produced, coalesce with pressure waves from elsewhere on the stator and form a spinning pressure pattern. Under right duct geometry, mean flow characteristics, and fluctuation frequency, these pressure patterns self-sustain and result in a propagating mode, called duct mode that eventually radiate to the far-field from engine exhaust. Most of the time, the modes decay in the fan duct and do not make to the far field. The aggregate contributions from all the duct modes create pressure field that is called the rotor-stator interaction noise.

This explanation holds for periodic vane fluctuations that result in discrete frequency interaction tones. However, for broadband vane pressure fluctuations, this explanation breaks down due to random amplitude/phase characteristics of vane-pressure fluctuations. To explain vane pressure fluctuations and rotor-stator interaction noise correlation, surface distributions of vane fluctuating pressures were measured as part of the Fan Noise Source Diagnostic Test (SDT) conducted in the NASA Glenn Research Center's 9- by 15-Foot Acoustic Wind Tunnel (Ref. 2). The SDT was on a model 22-in. fan of a modern turbofan engine (Figs. 3 and 4) consisting of 22 blades with design tip speed of 1215 ft/sec. Stator vane pressure time fluctuations were recorded using embedded pressure transducers along vane chord and span lines (Fig. 5). For each test condition, ~10 sec of data were recorded at 128 kHz sampling rate. Each test result set provided sound pressure spectral composition at each vane location point. As the number of transducers on the stators increases and as transducer locations on the rotor tips is considered, an alternate wireless data acquisition scheme was sought.

Wireless Noise Telemetry Task

An alternate data acquisition and processing scheme mimicking the emerging wireless sensor networks was adopted. The efforts at Antenna and Optical Systems Technology Branch at GRC included wireless telemetry link feasibility demonstration for vane source noise detection using Imote2 smart sensor motes and three noise sources including a microphone sensor. Nyquist sampling rate for noise signal 2 to 20 kHz asks for A/D ~50 kHz (20 µsec). The sensor signal through a power conditioning circuit on a "custom" interface board would modulate a 2.5 GHz RF carrier with digitized pressure data and import modulated data through the SPI port of Intel's smart sensor, Imote2 mote radio, for transmission. Received signal at the base station mote is sent to a host PC for signal processing and for displaying spectral components.

Kulite Pressure Sensor

Pressure sensors produce electric output proportional to the applied pressure. Kulite pressure sensors (Fig. 6) are piezoresistive transducers with response from near steady state to ultrasonic frequencies at 5 V and 200 Ω output impedance (Fig. 6). Device sensitivity is measured by (mV/psi). Because of the extremely small sensing element size (1.6 by 1.6 by 0.5 mm),

Figure 6.—Kulite pressure sensor.

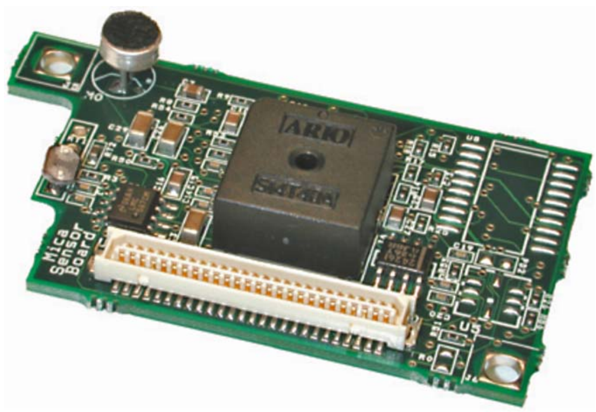

Figure 7.—Imote2's "basic" sensor interface board.

Kulite pressure sensors offer more packaging flexibility than any other technology for wind tunnel tests, flight tests, and other measurements of turbulent flow. Kulite sensors are also used in wind tunnel testing of automotive parts.

Imote2's "Basic" Sensor Interface Board

Sensor boards (Fig. 7), which can interface directly with Imote2 platform and operate through available open source software, exist for a variety of basic sensing applications such as light, temperature, pressure, humidity, and acoustic (sounder) sensors, and are compatible with most commercial sensing application needs for low frequency varying phenomena. On-board memory, A/D speed and resolution of these commercial boards do not support SFW sensor data acquisition needs at ~100 kHz sampling rate.

SFW "Custom" Sensor Interface Board

An alternate SFW sensor board concept for Imote2 were laid out that provides flexible user-selectable sampling rates and anti-aliasing filtering capabilities. Human hearing range of 2 to 20 kHz is considered with a focus around a 5 kHz 'duct-mode' (sampling rate, <20 µsec for a 1/5th scale engine testing). To avoid potential signal errors, avoiding sample-rate fluctuation is critical, especially in the higher frequency range, requiring microseconds sampling resolution. While simply interfacing a Kulite transducer with a high-quality A/D could address the sampling rate issues, a programmable signal conditioner was needed because of the flexibility it would offer in addressing anti-aliasing and signal processing concerns.

Embedded acoustic pressure sensors provide the ability to measure small-amplitude vane local pressure variations; therefore, sensor interface board must provide signal sampling resolution and noise characteristics. Several factors contribute to the quality of the measured digital signal output: the sensitivity of the given sensor, noise floor of the sensor and other electrical components, and the resolution at which the noise signal is sampled (A/D resolution) which dictates the smallest quantifiable measured increment.

The heart of the SFW acoustic sensor interface board is the Quickfilter QF4A512, a 4-channel A/D and programmable signal conditioner with user-selectable sampling rates and programmable digital filters (Ref. 3). The board interfaces a Kulite analog pressure sensor with the Imote2 via SPI I/O. A block diagram of the components of the SFW sensor board is given in Figure 8. Each component piece is discussed in the subsequent sections.

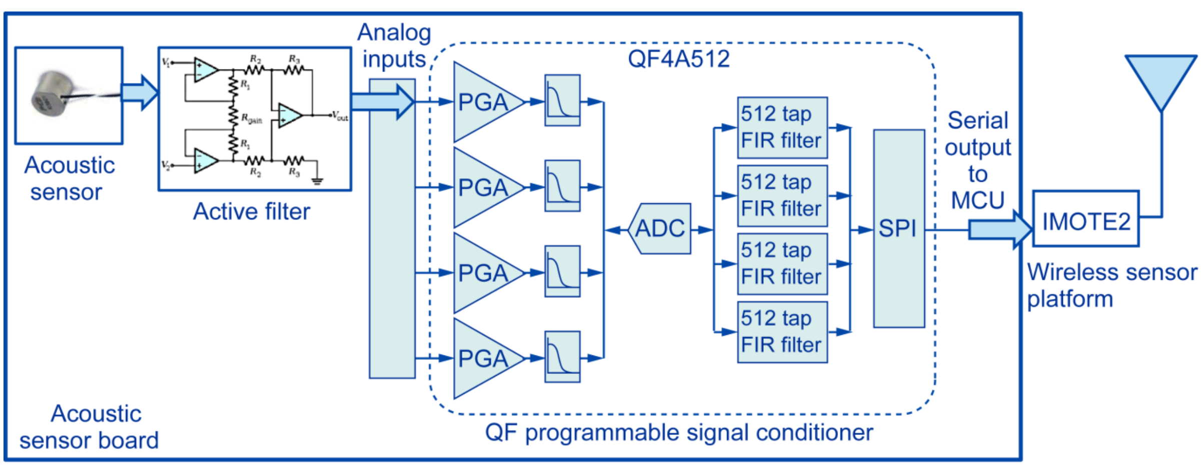

Figure 8.—Block diagram of SFW acoustic sensor interface board to Imote2 wireless platform.

Low-Pass Filter

Output impedance of the microphone sensor is fed to a low-pass filter and power conditioning circuit which acts as an initial slow roll-off anti-aliasing filter and an impedance matching device (Fig. 9).

The SFW acoustic power conditioning interface for noise measurement was used in the wireless link ‘feasibility demonstration’. The circuit components were operational amplifiers, resistors, ceramic capacitors, potentiometer and battery power to drive the microphone, as such, were only suitable for table-top demonstration. Though this was sufficient for a single, proof of concept link demonstration, a power conditioner circuit board has been fabricated to be miniaturized as a sensor interface board suitable for vertical integration to the Imote2 sensor platform.

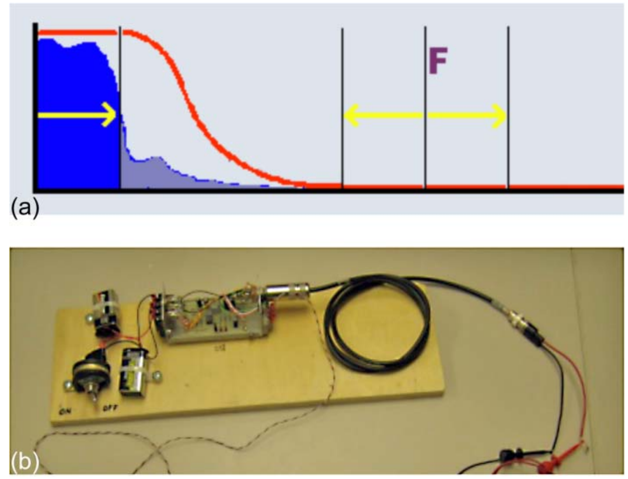

Figure 9.—(a) Low-pass filter characteristics and (b) SFW power conditioning circuit.

QuickFilter Development Kit, QF4A512-DK

The heart of the digital link development kit (Ref. 4) is the QF4A512 programmable signal conditioner with a 4-channel, 16-bit, Analog-to-Digital Converter (ADC).

Each of the 4 channels offers selectable gain, analog anti-aliasing filter, selectable sampling frequencies and individually programmable digital Finite Impulse Response (FIR) filters. The QF4A512 performs oversampling, filtering and decimation to achieve two goals (Fig. 10): improve output resolution by oversampling and thereby decreasing the quantization error noise and elimination of noise energy above the Nyquist frequency through a digital decimation filter. The gain, sampling rate and user desired FIR filter are designed through software provided by QuickFilter, by selecting specific FIR filter type, sampling rate and filter characteristics in the FIR Editor shown in the screen shot below. The filter is assigned to the channel and is exported to Imote2 header file when the sensing application is loaded onto the Imote2.

Imote2 mote possesses 32MB SRAM capable of supporting 50 kHz ADC sampling speed needed for SFW acoustic data. With 16-bit 4 channel-ADC, 32 MB SRAM would be able to handle 9 to 10 secs of acoustic time series signal. To cover 2 Hz to 20 kHz audible range, the biggest challenge was to achieve a 50 kHz (in µsecs) signal sampling rate through an ADC and higher power consumption capability (signal gain) from an interface board than can be measured by any commercial smart sensor board. For the current feasibility demonstration, we used a QF4A512 based custom sensor board, ISM 400, developed for structural vibration measurement (Ref. 5). First 3 channels of ISM 400 ADC were dedicated to acceleration sensing along x-y-z axes; the 4th ADC channel was utilized in this single link demonstration.

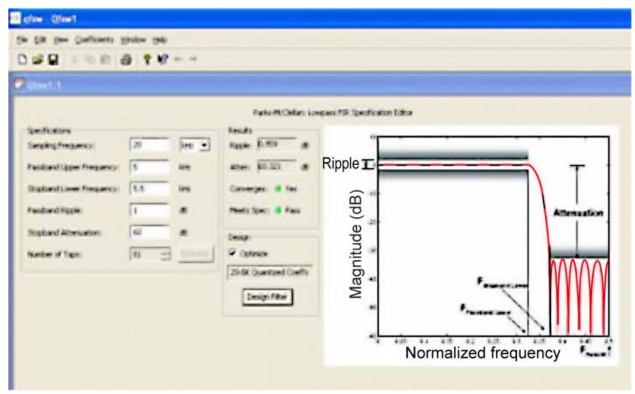

Figure 10.—Filter design screen and actual filter output from QF4A512.

Software Development

Programming for wireless motes is done in nesC language in TinyOS operating system to respond to commands (‘wake up’, ‘data acquisition’) issued by an application running on a PC that was developed in Java, and delivered wirelessly by a base station gateway mote. Some of the critical tasks done were software development for controlling the sensor board circuitry, modifying codes for driver control functions of the ADC, and designing filter components for signal processing optimization.

Some of the challenges were: programming in TinyOS to be able to import sensor data to the Imote2 radio’s overhead, transmit/receive serial data, multiplex, de-multiplex, and display parallel pressure data output spectrums.

Single Sensor Telemetry Link Feasibility Demonstration

The first set of single telemetry link feasibility demonstration was made using the SFW power conditioner and a custom sensor board, ISM400, with one of four ADC channels available while the other three were dedicated to the three axes of an on-board accelerometer sensor for vibration sensing. The signal sources were—simulated, random noise, and from a microphone. The table-top transmit-receive feasibility link set up is given in Figures 11 and 12 and the results are given in Figures 13 to 15.

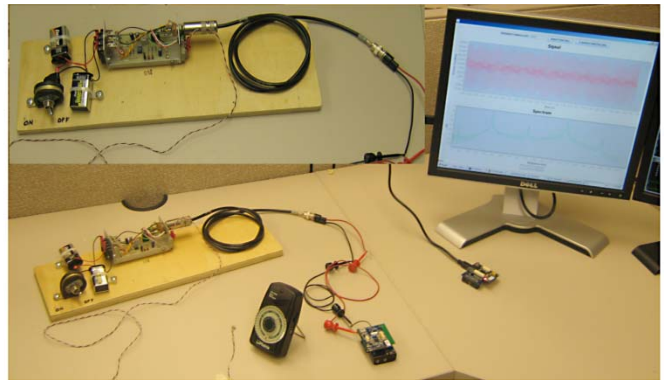

Figure 11.—Table-top link set up with transmit Imote2 to the left; receive base station Imote2 connected to a computer.

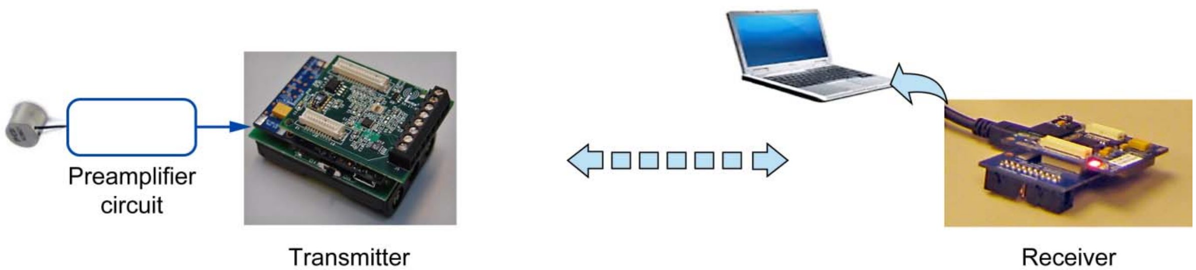

Figure 12.—Closeup view of the microphone connected to a transmit Imote2 that is placed away from a base station receive Imote2 connected to a laptop.

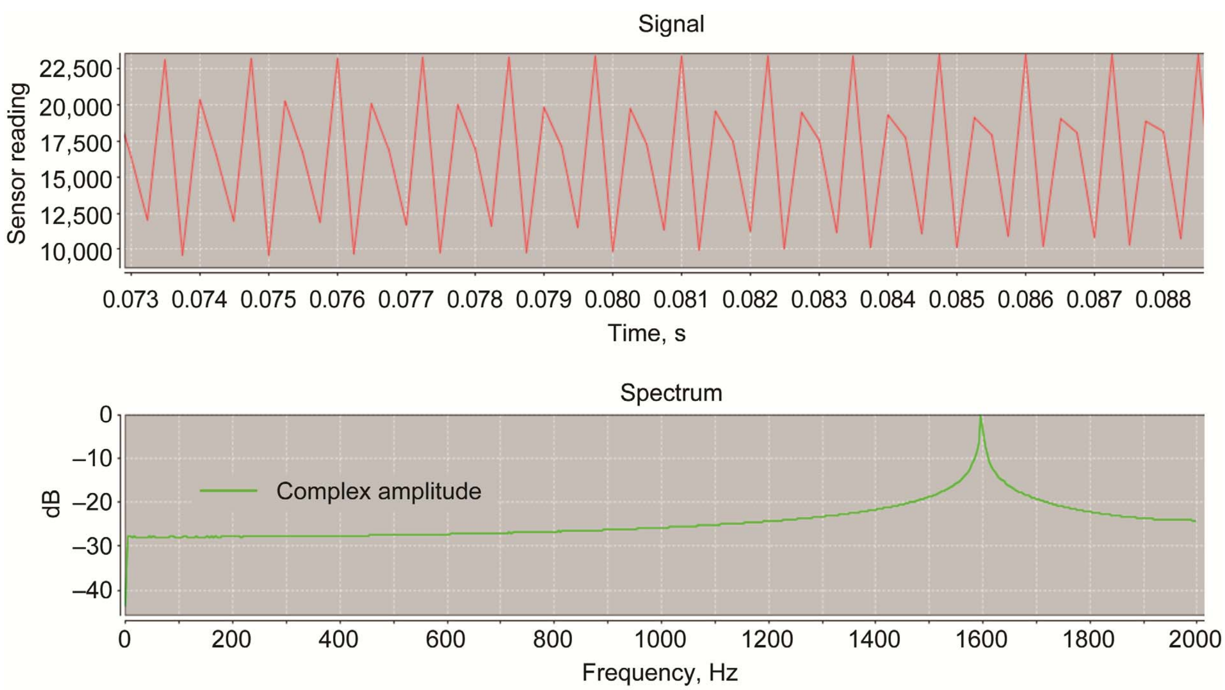

Figure 13.—1.6 kHz function generator wave and received signal spectrum at the base station.

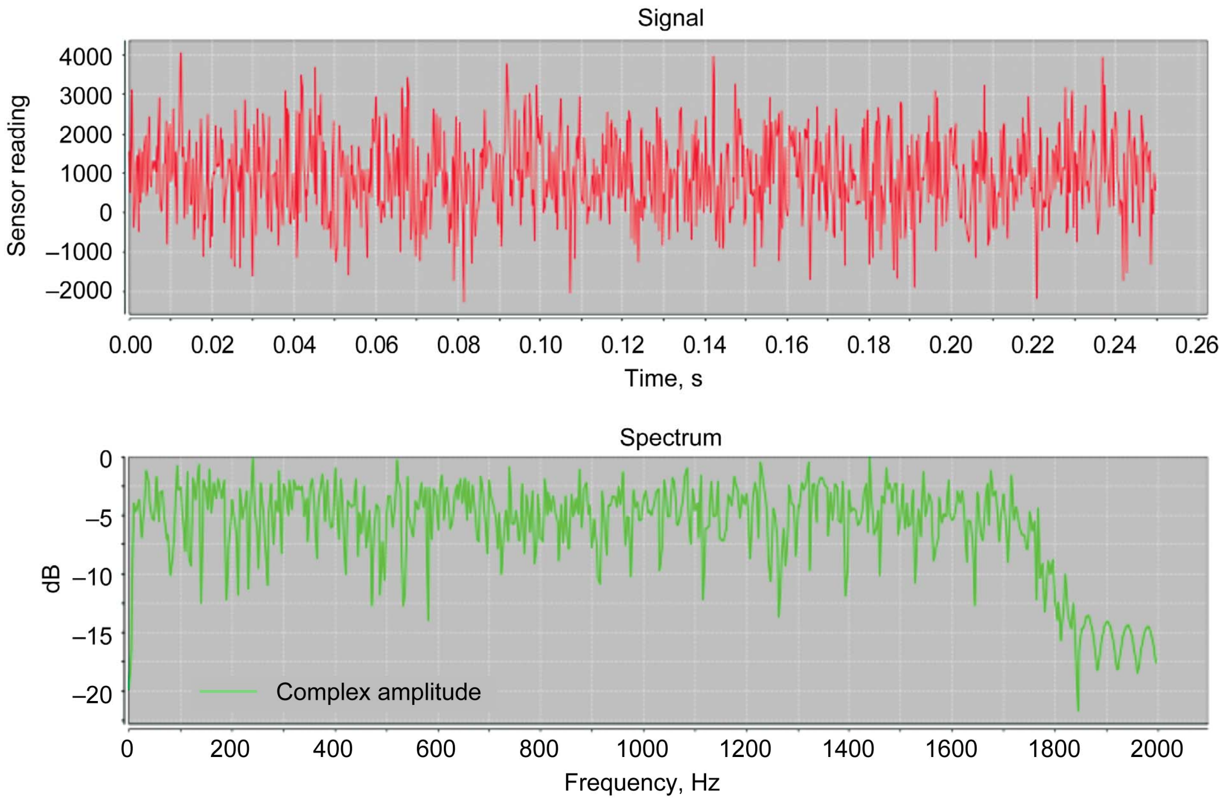

Figure 14.—White noise from PC and received signal spectrum at the base station.

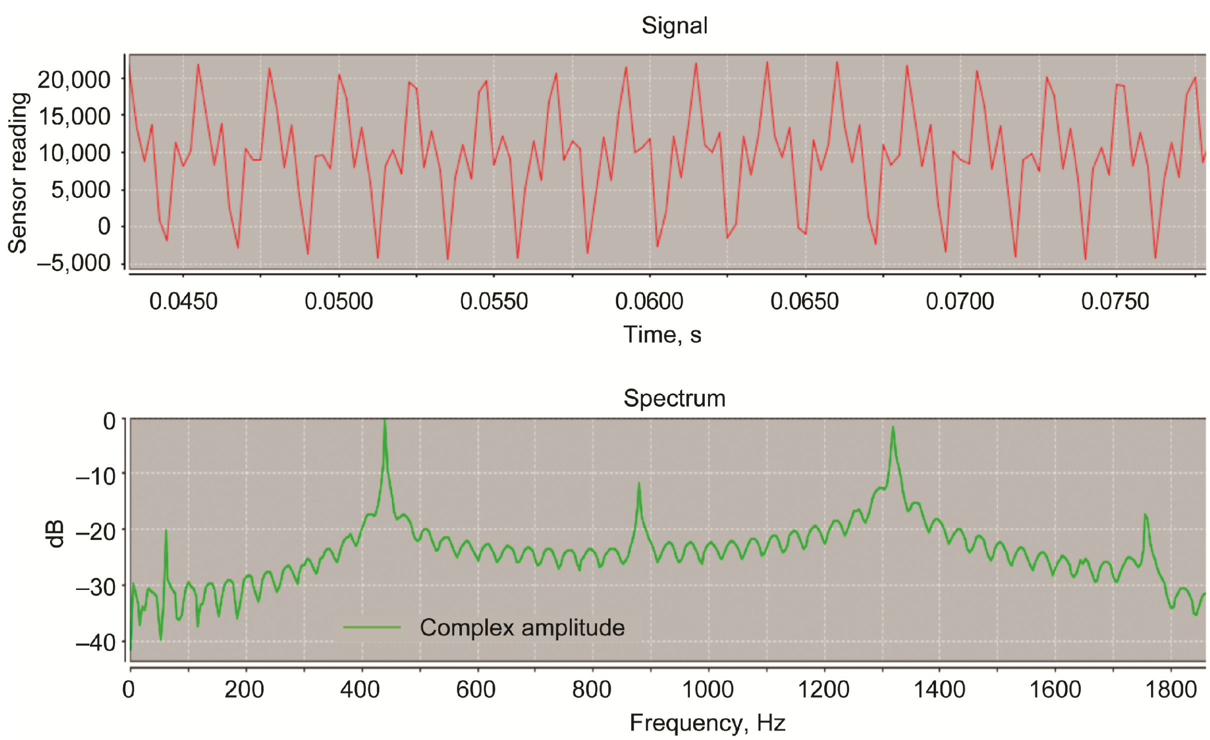

Figure 15.—440 Hz instrument tuner audio and received signal spectrum at the base station.

Concluding Remarks

Intel's Imote2 smart sensor radios provide enhanced computation and communication resources that make embedded acoustic sensor array data telemetry possible. This study has explored the development of a versatile Imote2 sensor interface board capable of onboard signal processing and suitable for SFW acoustic data telemetry applications. The components of the microphone sensor interface board have been selected to allow low-noise, high resolution, high-speed (µsecs) data acquisition necessary for successful implementation of multiple sensor links. Figures 13 to 15 summarize the results of three separate wireless link feasibility demonstrations that were conducted using the table-top set up of Figure 11. Acoustic signal time signatures for the case of an ideal signal, a random noise signal, and an audio microphone signal and the corresponding spectral distributions of signals received at the base station were recorded and displayed for various separation distances. These single-link demonstration results prove the feasibility of smart sensors for wireless data acquisition and processing in acoustic noise source detection problems.

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