Real-Time Wireless Pressure Sensing System for Stall and Loading Measurements in the Rotating Frame of Reference for a Low Speed Compressor

Maximilian C. Scardelletti, Senior Member, IEEE, Sameer Kulkarni, and Robert R. Romanofsky, Senior Member, IEEE

Abstract—In this paper the fabrication and characterization of a novel wireless pressure sensor system that can monitor and report real-time changes in pressure on the rotor blade of a low speed axial compressor is demonstrated. The pressure sensor was positioned on the second-stage rotor at approximately the mid-span location on the pressure surface of the blade near the leading edge and hard wired to a circuit box located on the center line of the compressor drum. The output of the pressure sensor is converted from a voltage to a frequency and transmitted wirelessly via circularly polarized antenna to a stationary antenna that was approximately 1 meter away, mounted at the centerline location on the inlet cart. The output signal was recorded on a spectrum analyzer with a LabVIEW program for data acquisition. Compressor rotation was ramped from 0 RPM up to its design speed of 1000 RPM and the airflow was decreased by closure of downstream throttle valve until the compressor stalled. The measurements from the wireless pressure system show increasing pressure as compressor flow rate is decreased, until a precipitous drop in pressure occurs which signals that the compressor has stalled.

Index Terms—Wireless pressure sensor system, pressure sensor, low speed axial compressor, cylindrical antenna.

I. INTRODUCTION

GAS turbine engines are widely used in power generation and propulsion applications, and the industry is continually seeking to increase power density. End users require safety, robustness, long machine-on times and component lifetimes, and flexible duty cycles, in addition to fuel efficiency. In its Aeronautics Strategic Implementation Plan, NASA has defined goals to simultaneously reduce fuel consumption, emissions, and noise [1] for future generations of large commercial air transports. For far-term commercial air transport, fuel/energy consumption reductions of 60-80% relative to a 2005 best-in-class airplane are targeted. To meet this goal, future propulsion systems using turbofan engines are envisioned with overall pressure ratios exceeding 50, bypass ratios on the order of 20, and combustor exit temperatures above 1540°C (2800°F) [2]. These conditions pose technical challenges in nearly every component of the engine in terms of material properties, thermal management, aerodynamic losses, and manufacturing limitations.

For example, extremely high temperature air exiting the combustor improves thermal efficiency but risks reduced life of blades in the high pressure turbine. Increasing overall pressure ratio to achieve fuel burn benefits requires very small blade spans in the rear stages of the high pressure compressor, which poses technical problems associated with reduced operability and stall, and aerodynamic efficiency deficits due to highly unsteady secondary flows from rotor-stator wake interaction, rotor tip clearance vortices, and corner separations. Concept vehicles utilizing distributed propulsors are envisioned to ingest the boundary layer of the airframe for fuel burn benefits, but this poses aeromechanical and operability challenges in the propulsors. Many of these risks may be greatly reduced if control systems can be deployed on future engines based on real-time diagnostics of relevant thermodynamic and structural properties. Such a system would require real-time, high frequency measurements made on rotating engine components, and with minimal weight added to the propulsion system.

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Measurements in the rotating frame are currently performed but usually with significant costs in terms of dollars and/or time, and the methods typically lack robustness and are limited to laboratory or research settings rather than on production engines. Methods based on pressure or temperature sensitive paints have been successfully deployed on rotating surfaces [3]–[7], but these methods require optical access and peripheral equipment such as cameras and lights. The paints also exhibit limited life after application and can degrade rapidly. Some rotating data systems store data on-board as in [8], [9], and the data is downloaded after the component has stopped rotating, but this method cannot be used to monitor conditions in real time. Real-time monitoring of rotating instrumentation has historically been done using slip rings or other similar systems [10]–[12]. Contactless systems are another method that can be used to transfer power and information and reduce some of the drawbacks that are inevitable with slip rings [13]–[16]. However, wireless transmission systems would greatly enhance the ability of real-time turbine engine monitoring systems. Wireless systems not only reduce cost, electronic requirements and weight but offer the ability to place sensors in unique, hard to access positions throughout the sensing environment, many of which are unachievable using conventional approaches.

Gas turbine applications require wireless sensors systems specifically designed for harsh environments. These systems can remotely send critical information back to a receiver that must be located outside of the harsh environment because of current electronic hardware inadequacies and reliability. Such systems include surface acoustic wave (SAW) temperature sensor system that record the temperature in a power plant chamber [17], pressure sensors with directional chip antennas [18] and structural health monitoring sensors [19]. However wireless sensor systems that can be used in rotational environments such as in compressors and turbine engines, where the sensing element actually rotates in a circular fashion at various temperature and pressure ranges have not been widely reported. Sexton, et al., offer one of the earliest reports on a wireless pressure sensor system for turbine applications [20]. The pressure sensor is attached to a rotor blade of a compressor and the data is transmitted to a stationary receive antenna. Unfortunately the system operating frequency is only 1 MHz which limits the speed of data transmission. This limitation is due to the electronics. The transmit and receive antennas consist of dipoles, which ultimately limits the utility of their design. In a rotational system, such as a compressor or turbine engine, where the antenna is spinning 360° a dipole will not allow continuous connectivity. The power loss is $|p_T \cdot p_R|^2$ where $p_T$ and $p_R$ are the transmit and receive electric field polarization unit vectors and the signal completely drops out when the antennas are orthogonal. Furthermore the data presented in the article shows the output as a function of volume flow rate vs. pressure for two speeds. There is no comparison to other sensors in the compressor to validate the output.

High frequency data transmission in real time is ideal but major challenges remain, including minimizing size and weight of the electronics package, questions on how to supply power, temperature limitations of electronics components, high-g accelerations, and signal quality concerns with a rotating antenna surrounded by the metal engine case. To that end, this paper details efforts to develop a wireless unsteady pressure measurement system in a laboratory setting with the goal of making useful real-time pressure measurements while trying to minimize power requirements and total weight and size of the electronics package. The wireless pressure sensor (WPS) system reported here utilized a pressure sensor that is attached to a rotor blade and hard wired to packaged electronics located near the center-line of the compressor drum. The application is a rotating compressor research rig, the Low Speed Axial Compressor (LSAC) located at NASA Glenn Research Center (GRC) in Cleveland, Ohio, where unsteady pressure measurements are intentionally induced on the surfaces of rotor blades to quantify useful aerodynamic information such as blade loading, flow separation, and stall. To the authors knowledge this is the first time an experiment such as this has been reported that combines all these attributes.

II. LOW SPEED COMPRESSOR FACILITY

To demonstrate the functionality of the WPS in a rotational environment, the system was characterized in the LSAC facility. The facility is used for aerodynamic performance testing and screening of advanced compressor technologies. The facility is shown in Figure 1. Unlike compressors in gas turbine engines, this research compressor is rotated via a 1,500 hp electric motor and variable-frequency drive. As the compressor rotor spins, ambient air is drawn into the facility through filtered roof vents. The air is conditioned for turbulence through flow straighteners and then passes through a calibrated bell mouth, where mass flow rate is measured, before entering the compressor. For a given rotational speed, the mass flow rate of air through the compressor is controlled by opening and closing a throttle valve downstream of the compressor which is closely coupled to the exhaust collector. The facility exhausts the air to the atmosphere far downstream of the last compressor stage.

The compressor consists of four repeating rotor-stator stages which are preceded by a row of inlet guide vanes (IGVs) as shown in Figure 2. The IGVs and first two stages establish a flow profile representative of an embedded stage in the high pressure compressor of a turbofan engine. The third stage is considered the research stage. The fourth stage is meant to buffer the research stage from the compressor exit conditions. The blade shapes and stagger angles referenced in previous work in this facility [21]–[23] were updated prior to the current effort, but other major features of the LSAC were unchanged. Rotor blade count was reduced from 39 to 37 rotor blades per stage, but IGV and stator vane counts remain at 52 per stage. The outer diameter flow-path remains at 48 inches and the blade span is 4.8 inches.

Relative to turbine engines, the LSAC operates at low rotational speeds of approximately 1000 RPM. Due to this low speed, the Mach numbers, pressure ratios, and temperature ratios in the LSAC are not representative of actual compressors in gas turbine engines. For instance, the overall pressure
ratio across all four stages is approximately 1.04 at the design point. However, other aerodynamic parameters such as non-dimensional blade loading, reaction, diffusion factor, and flow angle are engine-representative, allowing for relevant research on aerodynamic performance of the compressor airfoils.

Due to the relatively low rotational speeds, temperatures, and pressures, the operating cost is low and mechanical design is straightforward, allowing for implementation and evaluation of novel measurement techniques, use of plastic and/or additive parts, and rapid model changes.

### III. WIRELESS PRESSURE SYSTEM

The novel wireless pressure sensor (WPS) system was designed to monitor the real-time change in pressure on a scale of 0 to 0.2 psi. The measurements were conducted with ambient inlet pressure in the LSAC, which can range from roughly 14.2 to 15.3 psi throughout the year in Cleveland, Ohio. The WPS consisted of a pressure sensor, voltage divider, op-amp, voltage-controlled oscillator (VCO), circularly polarized antenna and infrared (IR) on/off switch. The circuits, integrated circuit (IC) sockets and batteries were secured to a perf board via mechanical fasteners, strapping or solder connections. The system was totally powered by batteries which are located under the perf board and enclosed within a metal package making the system truly wireless. The metal circuit box had dimensions of 12.5 cm by 10 cm by 7 cm. A circuit schematic and packaged pressure system are shown in Figure 3a and b, respectively.

Each component used in this pressure sensor system was individually characterized to determine its capability and limitations over the desired frequency band and how it would interact with the rest of the system. Bench-top testing of the packaged system was also performed to verify feasibility of operation of the system before integration into the low speed compressor. A Kulite ultra-miniature thin line pressure transducer (LPS-072) was used to determine approximately 0.2 psi pressure change in the LSAC. The compressor inlet air is at ambient pressure (approximately 14.4 psi on day of testing). The Kulite pressure transducer is an absolute pressure (sealed gauge), piezoresistive, Wheatstone bridge-based sensor and has a pressure sensitivity of 9.8 mV/psi. The sensor dimensions are 4.7 mm by 1.6 mm by 0.76 mm and has four wires to bias and provide output voltage (Figure 4a). The sensor ideally requires a 10V operational voltage and has a sealed gauge pressure range of 0 to 5 psi with an output voltage range from 0 to 50 mV. The sensor can detect changes in pressure as low as 0.001 psi. To determine the performance of the pressure sensor prior to testing in the LSAC, it was sealed in a chamber via a Conax compression seal fitting at ambient pressure.
pressure. The pressure was increased from 14.4 to 14.6 psi and the output voltage was recorded at steps of 0.01 psi. Figure 4b is a plot of the output voltage versus pressure with a DC bias of 9V (9V off-the-shelf alkaline battery). Ideally a 10V input power results in the maximum output voltage swing but a 9V battery was chosen for simplicity and practicality and to maintain the wireless capability. An off-the-shelf 9V battery is much easier to integrate into the pressure system than a custom-made 10V battery and requires less space and is much lower in price. The test was repeated 3 times to show repeatability.

The output of the Kulite pressure sensor voltage ranged from approximately 5.6mV at 14.4 psi to 7.1 mV at 14.6 psi, which results in a sensitivity of approximately 0.075 mV/0.01psi (7.5 mV/psi). Furthermore, the change in output voltage as a function of pressure from 14.40 to 14.6 psi was compared with a linear regression line where the correlation coefficient, $r^2$, was 0.999 indicating that the fit was extremely linear.

The sensor output voltage was too high to serve as an input voltage for the op-amp causing the op-amp to go into saturation very quickly as the sensor output voltage increased with increasing pressure. This limitation was due to the 12V off-the-shelf battery used to bias the op-amp. The 12V alkaline battery was chosen for its size, voltage output, cost and ease of integration into the packaged system. Consequently, another voltage must be introduced that could offset the sensor output voltage and reduce it to less than 1 mV which was more suitable for the op-amp input over the entire pressure range being tested. This meant that a voltage of approximately 5 mV was needed to offset the sensor output voltage. Since an off-the-shelf battery of 5 mV volts is not available, a voltage divider with a 1.5 AA lithium battery was designed to provide this voltage. The voltage divider resistors had values of $R_1 = 22 \, k\Omega$, $R_2 = 200 \, \Omega$ and $R_3 = 39 \, k\Omega$ and this resulted in a voltage across resistor $R_2$, the voltage divider output, of approximately 4.9 mV and when subtracted from the sensor output voltage resulted in a 0.5 mV voltage. Current draw (battery drain) was minimal. The operational amplifier used in this pressure sensor system design was an On Semiconductor LM358 single supply dual operational amplifier. It features low power drain, a common mode input voltage range extending to ground and single or split supply operation. The op-amp was made in a non-inverting op-amp configuration and the values for $R_1$ and $R_2$ are $3.9 \, M\Omega$ and $1k\Omega$, respectively. The gain of the op-amp with this resistor combination is $\approx 3900$. The output from the voltage divider was fed to the input of the op-amp and was amplified to a suitable level for the input of the voltage-controlled oscillator.

A Mini-Circuits ZX95-2750-S VC was incorporated into pressure sensor system design. The VCO has linear tuning characteristics over a frequency range of 2295 MHz to 2830 MHz. The phase noise is less than $-80$ dBc/Hz at 1 kHz offset and the phase noise decreases linearly to less than $-150$ dBc/Hz at 1MHz offset. The output of the op-amp was used as the tuning voltage of the VCO. To demonstrate the system a bench-top experiment was conducted.

A semi-ridged coax cable and SMA connector was used to connect the output of the VCO to a skew planar wheel circular polarized antenna. The skew planar wheel antenna has a $-10$ dB bandwidth from 2200 MHz to 2800 MHz and a return loss of $-17$ dB at 2440 MHz. The antenna has a gain of at least 2.3 dB across the bandwidth. A circular polarized antenna was required to ensure 100% data transmission as the WPS rotated 360°. As in [20], the dipole antenna was out of phase every 180° thus causing data retrieval intermittent. The output signal of the WPS was transmitted to another antenna of the same type positioned roughly 1 meter away. The output frequency of the pressure system was recorded using an Agilent N9020A MXA signal analyzer and data acquisition software and is shown as a function of pressure seen by the pressure sensor in Figure 5. The experiment was repeated three times to demonstrate reliability.

The WPS had an output frequency of approximately 2.32 and 2.62 GHz at 14.35 and 14.55 psi, respectively which resulted in a pressure sensor system sensitivity of 1.5 GHz/psi. This was also compared to a linear regression line and the correlation coefficient was 0.997 indicating a very good correlation between the output frequency data over this pressure range.

IV. MEASURED RESULTS

The Kulite pressure sensor was attached to a second-stage rotor at approximately the mid-span location on the pressure
surface of the blade near the leading edge as seen in Figure 6. The location of the WPS sensor on the rotor blade was chosen so that it was in relative proximity to the static pressure taps and was not driven by aerodynamic considerations. This proof-of-concept design is mainly focusing on whether the WPS can perform in a rotating environment on the low speed axial compressor, detect a change in pressure and a stall relative to the static pressure taps and transmit the data back to a receiver wirelessly.

The pressure sensor was connected to the circuit box, via hard wire, located near the centerline inside the compressor drum as shown in Figure 7. Once the compressor drum was sealed, two IR phototransistors (Vishay TEST2600 NPN) and a latching switch (American Zettler AZ850) were used to turn the pressure sensor system off and on to save battery life between testing cycles. The phototransistors were positioned at the forward face of the compressor drum on the rotor blade and hard wired to the latching switch in the metal circuit box located in the center of the compressor drum. The latching switch made it possible to open or close the ground loop of the circuit thus causing the pressure sensor circuit to be turned off or on when illuminating one of the phototransistors with a low power IR laser pointer. Illuminating the first phototransistor would turn on the circuit (closing the ground loop) and illuminating the second would turn off the circuit (opening the ground loop).

Compressor rotation was ramped from 0 RPM up to its design speed of 1000 RPM. At the design speed, the exhaust throttle valve was incrementally closed in order to generate the compressor’s performance characteristic curve, which is known as a speed line. The throttle valve was closed until the compressor stalled, signified by a large drop in pressure ratio at reduced mass flow rate. The pressure measured by the WPS was recorded throughout the incremental throttle valve closure, including into stall. For each discrete throttle position, the pressure from the rotating sensor was time-averaged and plotted against the compressor inlet mass flow rate, which was corrected to standard day values given the ambient humidity and temperature fluctuations measured in the facility. The WPS measurement was compared to an arithmetic average of four casing static pressure taps (CSPT), which are low frequency measurements that are located at the outer diameter of the compressor flow path, just upstream of the rotor 2 leading edge as shown in Figure 8.
The magnitudes of these two measurements are expected to differ since the sensors are measuring different regions of the compressor flow field. However, a comparison is made in order to show the trends of these two measurements across the flow range of the compressor, which should be similar. Both sets of measurements were normalized by the compressor inlet total pressure, measured just downstream of the flow conditioning elements in the inlet cart. These results are shown in Figure 9.

As expected, Figure 9 shows that the pressure measured by the WPS increases as the throttle valve is closed until the leftmost point, which was captured at the stalled condition and shows the steep drop-off in pressure ratio. This matches the trend exhibited by the steady casing static pressure taps. When the flow rate was 0.818, which is just before compressor stall, the pressure ratio from the CSPT and WPS are 1.0114 and 1.0155, respectively. Figure 9 shows that the WPS is measuring a higher pressure, the difference being due to its location on the pressure surface near to the blade’s leading edge indicating that the position of the WPS offers new insight into pressure flow characteristics of the compressor.

Figure 10 presents time traces of the pressures measured by the WPS and by the casing static taps at various conditions. Time traces of these pressures are shown at the design point condition in Figure 10a, and at a pre-stall condition in Figure 10b. As expected, the absolute pressure level of the WPS measurement is higher at the pre-stall condition as compared to the design point condition. The CSPT and WPS average pressure readings at the design point condition are 14.559 and 14.572 psi, respectively. The WPS measurement goal was to characterize changes in pressure over a pressure range from 0 to 0.2 psi in steps of 0.001 psi. The percent difference between the WPS and CSPT for this comparison was roughly 2.3%. It is evident that both measurements are capturing the small unsteady pressure fluctuations in the compressor at this condition. The average pressure readings for the CSPT and WPS at the pre-stall condition are 14.603 and 14.671 psi, respectively which is a percent difference of roughly 10.7%.

In Figure 11, time traces of the WPS and casing static taps are plotted as the compressor is throttled into stall. Both measurements show the gradual increase in total pressure as the throttle valve is closed. As the stalling condition is approached, we see that both measurements indicate a plateauing of the pressure rise, and then a sharp drop-off in pressure which indicates that the compressor is stalled.

These results show that the WPS tracks the pressure trends of the CSPT measurements but differs in magnitude as the pressure increases due to reduced air flow caused by closure of the exhaust throttle valve. The change in pressure when
the compressor is in the throttled state and just before the compressor stall state is 14.150 and 14.092 for the WPS and CSPT, respectively which is a 48% difference and is nonlinear. The sensors are measuring different flow features within the compressor as indicated by the nonlinear difference between the measured pressures across the operating range of the compressor.

The measurements meet expectations based on understanding of compressor flow physics in the literature. The life of the WPS and electronics package proved to be adequate, and battery duration is sufficient for typical measurement durations. The next generation of the WPS is under development and the goals are to increase frequency of the data acquisition rate and to expand channels to allow for multiple simultaneous measurements from an array of sensors mounted on the rotor blade. High-frequency measurements of pressure fluctuations around the surface of the rotor blade would give critical information on aerodynamic loading, boundary layer separation, and incidence. These insights are sought after as compressor designers look to advance the state-of-the-art health management of gas turbine engines.

V. Conclusion

A novel wireless pressure sensor system was developed to monitor and report real-time changes in pressure in a low speed axial compressor in an effort to increase the life-span by eliminating premature tear down and inspection of gas turbine engines. The wireless pressure sensor system incorporated a Kulite ultra-miniature thin line pressure transducer which was used to determine approximately 0.2 psi pressure change in the compressor as the airflow was reduced to cause an engine stall. The sensor was positioned on the leading edge of a rotor blade and hard wired to a circuit box located on the center line of the compressor drum. The output of the Kulite pressure sensor was converted from a voltage to a frequency and transmitted wirelessly via circularly polarized antenna to a stationary antenna that was approximately 1 meter away, mounted at the centerline location on the inlet cart. The output signal was recorded on a spectrum analyzer with a LabView program for data acquisition. The system was turned on/off using IR phototransistors and a low power IR laser pointer.

The WPS measurement was compared to an arithmetic average of four CSPTs, which provide low frequency measurements from wired pressure sensors that are located at the outer diameter of the compressor flow path, just upstream of the rotor 2 leading edge. A comparison between the WPS and CSPT shows the trends of these two measurements across the flow range of the compressor are similar but differ in magnitude. The WPS pressure levels are consistently higher. However, the difference in pressure levels is expected due the different sensor locations. Also, as the flow rate is reduced further the difference in magnitude increases non-linearly. Positioning the WPS in regions of aerodynamic interest, such as locations where flow becomes separated, could provide invaluable information that can add insight to aerodynamic loading, boundary separation, and incidence in a turbo fan engine. Repeating these measurements at different locations of aerodynamic interest on the rotor blade is left for future work. Impact of temperature on the WPS should be quantified if the sensor is applied in more engine-representative high temperature environments. The temperature sensitivity was not considered in the current work, as the temperature rise is negligible due to the nature of the low-speed research compressor.

The WPS in this effort is of relatively low cost and low complexity. In our experimental setup, the wireless system had minimal routing requirements for instrumentation and electrical leads, which could be incorporated without any major changes to the compressor shaft or drive line components. The compact packaging of the electronics simplified installation onto the compressor rig.

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