AN EMBEDDED WIRELESS DATA ACQUISITION SYSTEM FOR WIND TUNNEL MODEL APPLICATIONS

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ABSTRACT

An in-model data acquisition system has been developed that can accept inputs from various sensors and transfer the data wirelessly to an access point outside a wind tunnel's test section. This system was developed as a potential alternative to the current state of wind tunnel data collection, which requires the use of long lengths of cable carrying low-level sensor signals that are extremely susceptible to induced noise. In addition, present methods of retrieving data require that multiple cables be routed across the balance, creating alternate load paths. With the advent of wireless data transfer, not only are these two items addressed, but also the reduction of external cables to the model will reduce wind tunnel model installation time as well as the cost of operation.

This paper will describe the results of two separate wind tunnel tests, conducted at NASA Langley's Transonic Dynamics Tunnel and the 16-foot Transonic Tunnel, in which this new embedded system was used to collect data from typical aerodynamic measurements. The recorded results from these wind tunnel experiments include data from pressure, model attitude, temperature, and force balance transducers.

INTRODUCTION

Today, no aircraft, spacecraft, space launch or reentry vehicle is built or committed to flight until after its design and components have been thoroughly tested in wind tunnels.[1] With this high demand for wind tunnel test time, the importance of reducing model installation time as well as improving system usability becomes apparent. An ideal concept to address this problem would be a "plug and play/test" model. This concept would entail a model that is completely instrumented, has onboard signal conditioning and analog to digital conversion, and uses a wireless telemetry system. Such a model could be "plugged" into the tunnel mounting hardware and be ready to test.

A system in its most general form, is defined as a combination and interconnection of several components to perform a desired task.[2] In a physical environment (wind tunnel or other aerodynamic experiment) the signal processing system is linked to various signal sources, e.g. electric, magnetic, mechanic or acoustic sensors[3]. This paper will describe a data acquisition system with various signal sources and will detail the test arrangement as well as describe the experimental results of two separate wind tunnel tests.

While a variety of wireless data systems have been available worldwide for a number of years, their current popularity has increased dramatically. A rising number of business users are starting to take advantage of these systems, with consumers not far behind. This upsurge is driven by a number of powerful market forces, including high penetrations of cellular-phone usage, data services for cellular networks, powerful new portable computing platforms, smaller wireless devices, microbrowsers, and important communications standards[4]. Despite these advancements in wireless technology, still no commercially available system exists today designed for the extreme conditions encountered in wind tunnel testing.

In an effort to promote this "plug and play/test" concept there are three novel components used for this new data acquisition system; they are the MEMS (MicroElectroMechanical Systems) sensors, embedded electronics, and RF (Radio Frequency) wireless telemetry. The signals from the sensors are digitized on-board the model and transmitted using microwave telemetry. Data are collected and displayed real time on

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a standard personal computer with commercially available software that was customized for this application. Commercially available MEMS sensors were selected for their small size and relative low cost, to be compared with conventional sensors. These smaller sensors provide a larger applications base, with the ability to fit into smaller models that cannot house most standard instrumentation. A custom data module was designed and fabricated in-house to meet sensor resolution and physical constraints. This data module allows analog signals from various sensors to be digitally processed onboard the model and then transferred serially to the telemetry unit. The wireless telemetry system is a commercially available unit that was customized for wind tunnel applications. With the use of high gain antennas this telemetry scheme could adequately provide both the transfer rates and signal strength needed to reliably send data to a receiving unit outside the tunnel test section.

The reliability and robustness of this system has been shown with long-term operation (3 weeks) in a wind tunnel environment. Also prior to tunnel entry the system was evaluated at temperatures up to 75°C and vibrated to 5.4 G rms. Through these tests as well as comparing the data collected to conventional methods the advantages of a new embedded data acquisition system become evident.

EXPERIMENTAL SETUP

TDT Test

This section will discuss two separate experiments conducted at the NASA Langley Research Center. The first experiment was performed at the Transonic Dynamics Tunnel (TDT). This is a unique facility dedicated to identifying, understanding, and solving aeroelastic problems. The TDT is a closed-circuit, continuous flow, variable pressure wind tunnel with a 16-ft square test section with cropped corners. The tunnel is capable of using either air or R-134a as the test medium and can operate up to Mach 1.2 and at stagnation pressures from near vacuum to atmospheric[5].

For this experiment both air and R-134a were used as test median. Figure 1 depicts the overall setup of the system and shows the general location of system components in relation to the model. As shown in Figure 1, data is transmitted from the model through an expansion joint in the floor of the test section to a receiving telemetry unit in the plenum. Also it can be noted that the digitized data are being sent serially from the plenum to the War Room (a remote location at the TDT used for expanded customer system setup).

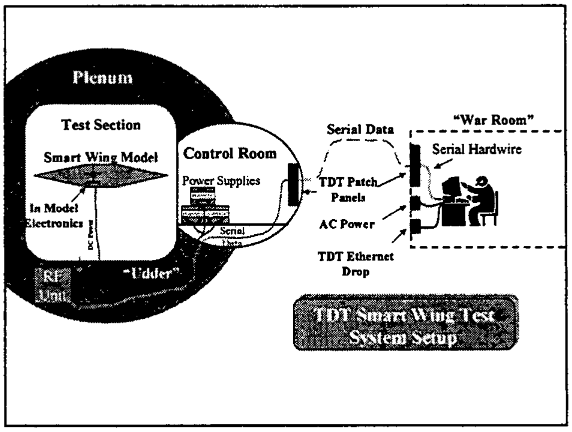

Figure 1. *System setup for the Smart Wing test at TDT*

This experiment "piggybacked" on the first Phase 2 test of the DARPA/AFRL/NASA/ Northrop Grumman Smart Wing model program. There were several advantages of testing with this particular model. The size of the model was relatively large (approximate 9.3-foot wingspan), and because of this, several independent systems could be housed in the fuselage and tested during this wind tunnel test. This model also had a composite outer covering, which allowed for RF data to be transmitted through the skin of the aircraft, with no external antenna. This lends itself to the ideal situation of ultimately having no cables or wires external to the model.

Figure 2 depicts the system block diagram for the TDT test. The data path can be followed from the signal source (transducers) on the left, then into the embedded electronics, then onto the RF transceiver. At this point the data are received in the plenum area and sent using a RS-485 serial protocol to a laptop computer with customized software. Note that there are three different physical parameters being measured in this configuration: angle of attack, static pressure, and the temperature of the embedded components.

16ft-TT Test

The second experiment reported in this paper was performed at the 16-Foot Transonic Tunnel (16ft-TT). This is an atmospheric, closed circuit tunnel with a Mach number range of 0.2 to 1.25. The test section of the tunnel is octagonal with a distance of 15.5 ft across the flats[6]. This experiment used a NASA, High Speed Research (HSR) model as its test bed. The size of this

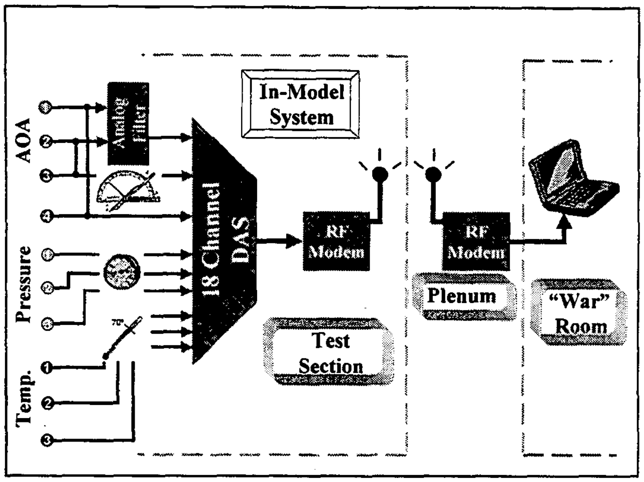

Figure 2. *System Block Diagram for TDT Smart Wing Test*

model is much smaller as compared to the Smart Wing model (approximate 2-foot wingspan) and only allowed for a 3-inch cross-section in the fuselage to house the embedded electronics and telemetry.

Figure 3 is a photo of the model mounted in the test section and depicts notable items. For this test both an embedded antenna in the model's canopy and an

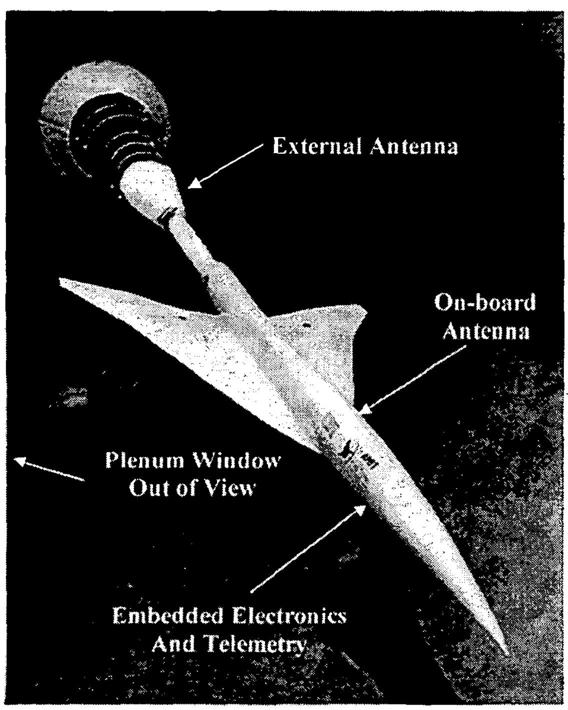

Figure 3. *HSR Model in 16ft-TT*

external antenna were investigated. Unlike the previous test, this model was constructed entirely of metal and did not lend itself to transmitting RF signals through the model skin. Figure 3 shows the location of a flush mounted, on-board antenna that was embedded beneath the canopy surface, so not to cause any aerodynamic anomalies. Data was transferred from one of these antennas, in the test section, to a receiving antenna in the plenum area. The 16ft-TT test section has a glass window for optical access; this is where the receiving RF unit was mounted (just out of frame in Figure 3). As in the previous test, data are sent from the receiving RF unit to the control room using a serial RS-485 protocol.

Figure 4 depicts the system block diagram for the 16ft-TT test. Once again, the data path can be followed from the signal source, on the left, then into the embedded electronics, then onto the RF transceiver. At this point the data are received in the plenum area and sent using a RS-485 serial protocol to a laptop computer with software specific to this test. Note, that this system was designed to measure primarily the signals produced by typical wind tunnel force/balance instrumentation (6 channels of strain, two temperatures and an excitation voltage).

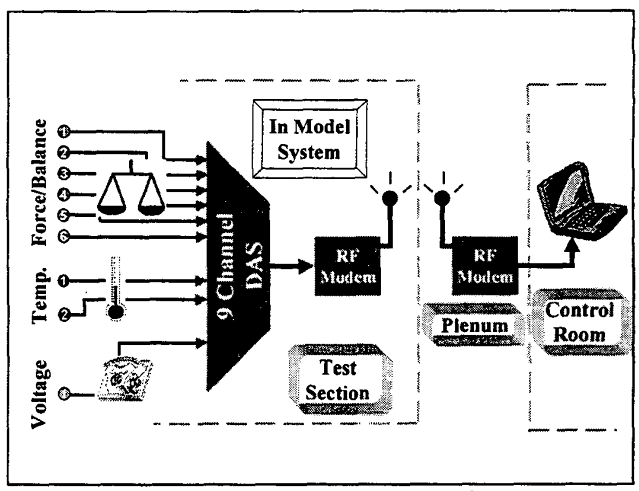

Figure 4. *System Block Diagram for 16ft-TT HSR Test.*

For this test a second generation embedded electronics package was designed and fabricated. The major differences in this package and the TDT package are a reduced channel count and the absence of analog filters (evident in Figures 2 and 4). The purpose of these changes are to meet the smaller size criteria of the HSR model. Also, a lesson learned from the Smart Wing test was that for low frequencies (less than 10Hz) the onboard digital filtering of the embedded electronics is adequate and less sensitive to thermal drift.

Embedded Components

There are three unique components to this data acquisition system; they are the MEMS sensors, embedded electronics, and RF wireless telemetry (Figure 5). The MEMS sensors selected for this test are commercially available, and have to advantage of small size and relative low cost. The smaller sensors ranged in size, from attitude sensors that measure 27x28x6mm to pressure sensors that measure 3.2mm diameter. An embedded data module was designed and fabricated in-house to meet sensor resolution and physical constraint requirements. The overall dimensions of the electronics package are 32x60x16mm, for the 9-channel module. The wireless telemetry system is a commercially available unit that was customized for wind tunnel applications. With the use of high gain antennas this telemetry scheme could adequately provide both the transfer rates and signal strength needed to reliably send data to a receiving unit outside the tunnel test section. The overall dimensions of these units are 102x60x25mm.

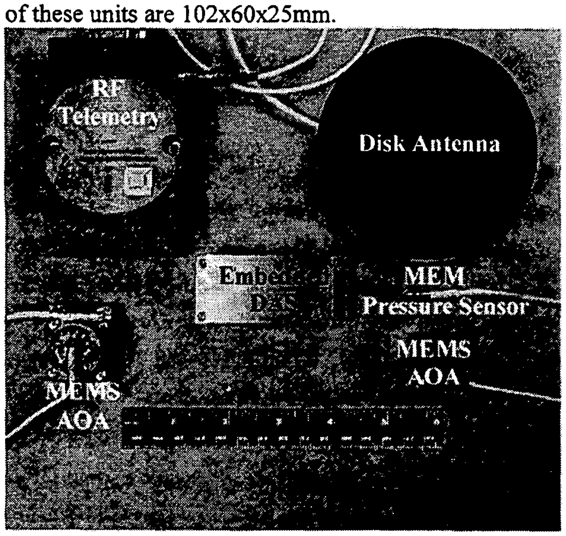

Figure 5. *In-Model Data Acquisition System*

In-Model DAS

The In-Model Data Acquisition System (DAS) has several advantages over the typical DAS used in most wind tunnels. One significant advantage is that the overall signal to noise ratio will be improved because the transducer cables are very short (inches compared to tens or hundreds of feet). In the typical system expensive instrumentation amplifiers and special purpose cables are used to negate the electromagnetic interference imposed on long cables.[7]

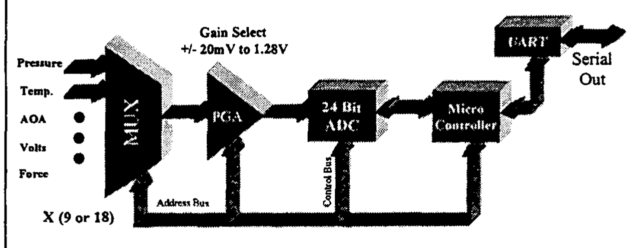

Figure 6. *Functional Block Diagram of In-Model DAS*

The functional block diagram for these DAS modules is shown in Figure 6. The functionality of both the 18 channel and 9 channel DAS units are the same, only the number of channels change. As depicted, various voltage signals can be connected to the in-model DAS. This is possible because of the unit's ability to route the multiplexed analog signals to a programmable gain amplifier. This allows the DAS to change ranges to optimize resolution (+/-20mv to +/-1.28V). Next, analog signals are sent to a 24-bit analog to digital converter where the signals are digitized and sent out on a serial bus.

The DAS unit also has an onboard micro-controller to manage such things as multiplier timing, range setting, ADC (analog to digital converter) setup, data throughput, and handling incoming communications from a host computer. In general (for most range and filter settings), this unit provides a 100ppm or 0.01% of full-scale output, with a 500 nanovolt noise floor, as shown in Tables 1 and 2.

Table 1 *Embedded DAS Analog Specifications*

Range	Embedded DAS Accuracy	
+/-1.28V	100ppm	0.01% FS
+/-640mV	100ppm	0.01% FS
+/-320mV	100ppm	0.01% FS
+/-160mV	100ppm	0.01% FS
+/-80mV	100ppm	0.01% FS
+/-40mV	100ppm	0.025% FS
+/-20mV	100ppm	0.025% FS

Table2 *Embedded DAS Noise Floor*

Range	Noise Floor	Bit Resolution
+/-1.28V	1×10^{-6}	2^{22}
+/-640mV	0.5×10^{-6}	2^{22}
+/-320mV	0.5×10^{-6}	2^{21}
+/-160mV	0.5×10^{-6}	2^{20}
+/-80mV	0.5×10^{-6}	2^{19}
+/-40mV	0.5×10^{-6}	2^{18}
+/-20mV	0.5×10^{-6}	2^{17}

EXPERIMENTAL METHOD

TDT Test

As mentioned earlier, the DARPA/AFRL/NASA/Northrop Grumman Smart Wing model provided an excellent test bed to develop this new embedded system. The technical objectives for the system during this test were as follows:

- Evaluate embedded DAS system in tunnel environment.
- Validate MEMS sensors as compared to conventional sensors.
- Verify wireless telemetry system in multipath environment.
- Acquire synchronized data for analysis.

Mounted onboard the Smart Wing model were 10 MEMS sensors, an embedded DAS system, and the onboard telemetry unit. The goal was to acquire data for every test condition and compare the results to the data collected by the standard TDT DAS from the corresponding "conventional transducers. For this test the Mach number was varied from 0.25 to 0.8 and model attitude was varied from –6 degrees to 15 degrees. Model attitude was recorded using two differing technologies of MEMS inclinometers and compared to the standard three axis, angle of attack sensors used at TDT. The MEMS attitude sensors were used with both analog as well as digital filtering (shown in Figure 2). Three MEMS pressure sensors were used to analyze orifice pressures, which were compared to symmetrically opposed orifices on the adjoining side of the fuselage. MEMS temperature sensors were used to monitor and provide a means for real time thermal corrections of the displayed data.

A stand-alone data system was developed to display and record real-time data as well as tunnel test parameters. This system was remotely triggered by the TDT data system to ensure that each data set was synchronized to tunnel data for posttest analysis. This stand-alone DAS was configured for autonomous operation, that is to say, that for a 3-week period the system recorded data without the need of a DAS operator.

Some of the difficulties encountered during this test were such items as occasional RF signal dropout. This was due to the multipath environment in the test section, as well as transmitting the RF signal through not only the outer skin of the model but also through a small expansion slot (approximately three inches) in the floor of the test section. The RF dropout proved to be a function of model attitude and signal loss was limited to a small range of pitch. Another notable difficulty was the thermal instability of some of the MEMS inclinometers. This will become apparent in the data reported in the results section.

16ft-TT Test

Unlike the Smart Wing test, the 16ft-TT HSR test was designed solely for testing the embedded DAS telemetry system. The focus of this test was narrowed to concentrate primarily on acquiring force/balance data and the related measurements. For this test a smaller version of the 18-channel DAS unit was required to fit into the canopy area of the HSR model. The result of this refinement yielded a 9-channel DAS unit for measuring the six components of a force/balance transducer, as well as the two temperature transducer readings and the excitation voltage.

One of the concerns for this test was that the embedded DAS unit would be measuring the same signal source simultaneously as the 16ft-TT DAS (both systems in parallel across the strain gage bridges of the balance). The concern here was that the embedded DAS would create superfluous loading or switching noise onto the small signal being read by the tunnel DAS (+/-5mV max.). This issue was addressed before tunnel entry in the model build-up area of the 16ft-TT. By comparing both systems to the results of a calibrated source, the results that the error induced by the embedded DAS system was below the discernible noise floor of the tunnel DAS.

As mentioned earlier, the HSR model is completely constructed of metal and hence does not allow for RF transmission through the skin of the model. This prompted another study, to attempt to transmit the RF signal from an antenna embedded in the canopy of the model (see Figure 3). The results showed that a data link could be established over the short transmission distance (approximately 8 feet), however this configuration tended to be much too sensitive to model attitude, and the secondary antenna mounted on the model sting was used instead (Figure 3).

The data collection system for this test was configured in a similar manner to the Smart Wing test. Again, data recording was synchronized and real time data were displayed in both raw and engineering units.

One of the difficulties encountered in this test was similar RF signal dropout, just as observed in the Smart

Wing test. Using the secondary disk antenna did minimize this effect, however there was still a small polar region (approximately 2 degrees) in which it was difficult to maintain a reliable data link. Another problem was trying to match the 16ft-TT analog filter setting to the embedded DAS's digital filtering scheme. This is necessary since the dynamic element of a wind tunnel balance can be an order of magnitude higher than the static signal source. The digital filters were set to a relatively low value (1Hz), to try to resolve static values from the dynamic signals. It becomes important to match filter settings as closely as possible to eliminate any aliasing effects.

RESULTS

The results of the TDT Smart Wing test are documented in this section. Figures 7 and 8 are representative plots of the angle-of attack and pressure data acquired during the test and is indicative of data sets from the entire test. Figures 9 and 10 show the uncertainties associated with these measurements.

The results of the 16ft-TT HSR test are also documented in this section. Figure 11 depicts the overall uncertainty of the entire test, as compared to the tunnel DAS data.

The data illustrated in Figures 7 and 8 show the results of the embedded system as it compares to conventional tunnel measurements techniques used during the Smart Wing test. Figure 7 depicts sample results of angle of attack data at Mach 0.8 acquired during the Smart Wing test. Here can be seen that the data tracks well with tunnel attitude data, giving less that a 3% full-scale error for all 6 channels (tunnel data is shown as solid line). The TDT AOA standard for this test provided an accuracy of 0.05% full scale. The embedded system error is shown in Figure 9 for the 6 angle of attack channels recorded (4 separate MEMS sensors, with two additional channels for analog filtering, see Figure 2).

Closer inspection shows that 4 of the 6 channels have a larger bias error; this is the result of thermal drift of both the sensors and the analog filters. Note: the 2 channels producing the best accuracy (less than 1%) are the 2 channels that were digitally filtered.

Figure 8 depicts the pressure data acquired at the same tunnel conditions for the same Smart Wing test. This data represents 3 orifices along the aft section of the fuselage, and is compared to 3 co-positioned ports on the opposite side. Because of this, and the fact that the Smart Wing model has an asymmetric design, the data cannot be a direct comparison but should track the tunnel data closely, and Figure 8 shows that this is the case. Again the solid lines represent TDT data. Figure 10 shows that this pressure data tracks better than 0.5% full-scale as compared to tunnel data. The tunnel pressure standard for this test provided an accuracy of 0.05 % full scale.

Figure 11 depicts sample results of the 16ft-TT HSR test; in this case model force/balance signals are the measurand. As seen on the plot, results compare to within approximately 1% full-scale of the standard tunnel measurements. The balance for this model provided an accuracy of 0.4% full-scale worst case. This data includes Mach number sweeps from wind off to 0.8, as well as attitude sweeps from 0 to 15 degrees. All reported data in this paper have been synchronized to the wind tunnel DAS units to insure that the data that was compared encompassed the same temporal window.

To compare the results of these experiments to a given standard is a difficult task. Many items have been mentioned already that would cause a variance in data from a current measurement standard. Some of the other sources of error include such things as, irregular calibration and re-zero cycles for the embedded DAS, possible EMI noise from other on-board systems, and systemic problems such as installation and operational anomalies.

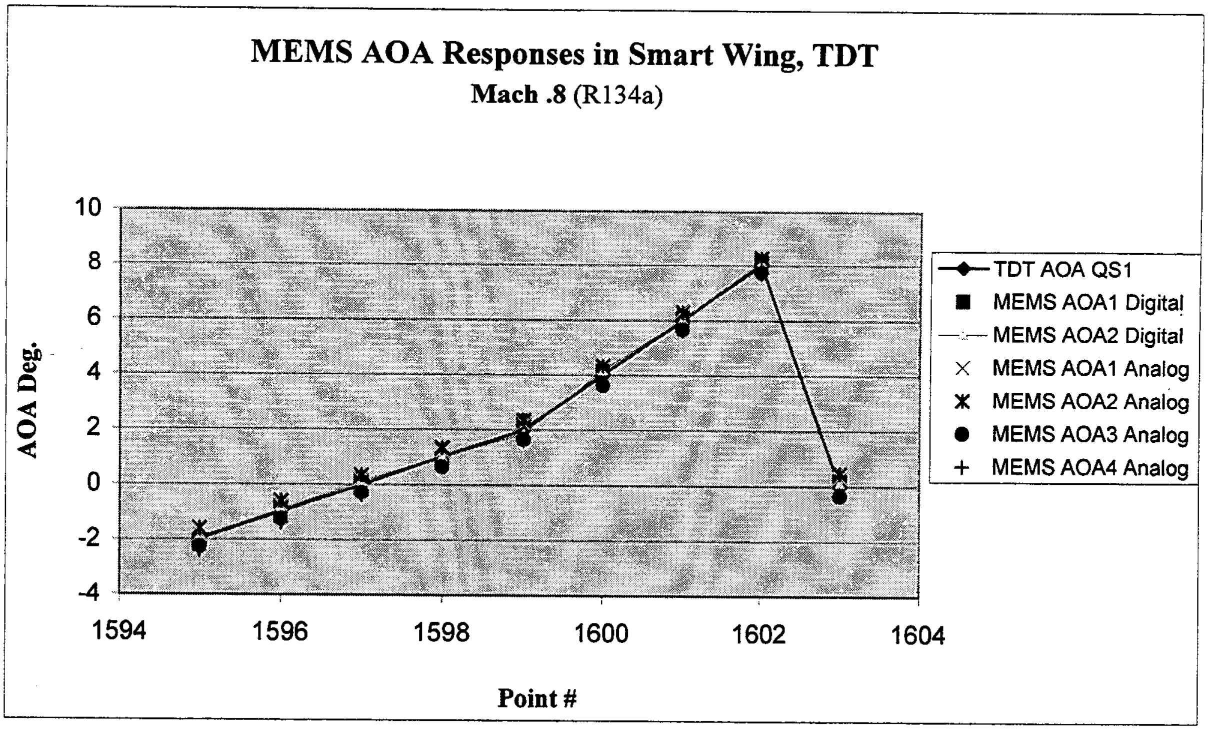

Figure 7. *Example of MEMS Attitude Data as compared to Wind Tunnel Data for the Smart Wing Test*

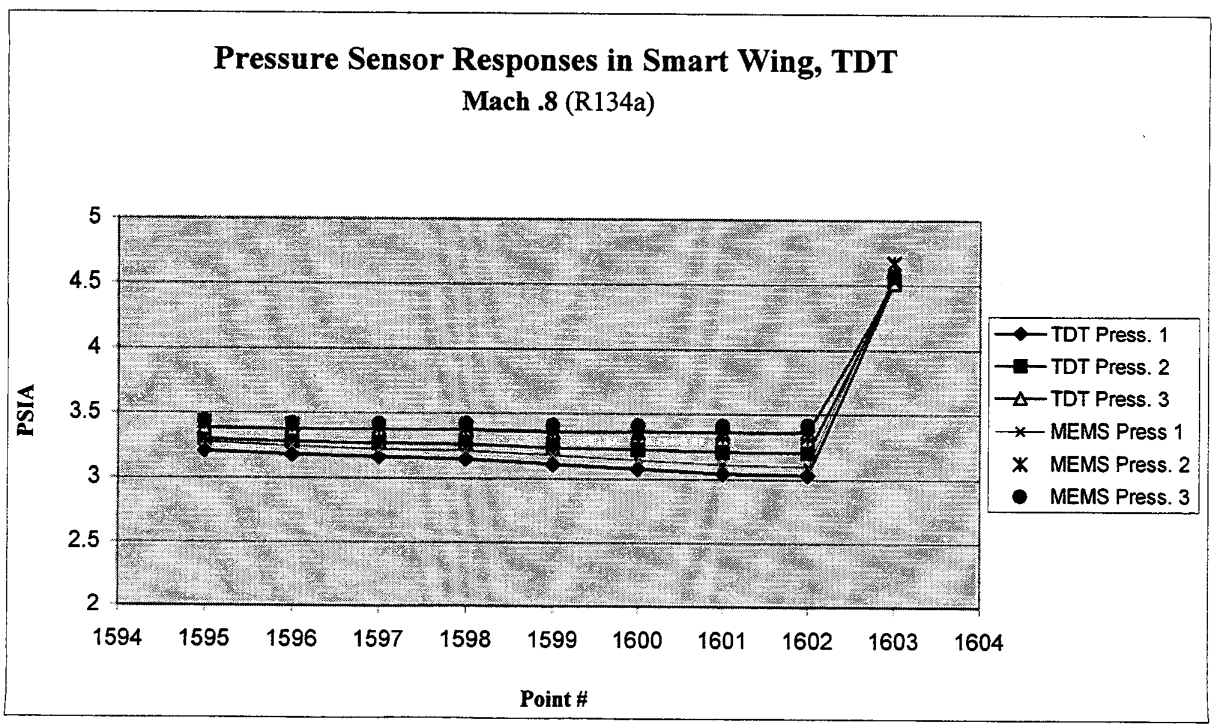

Figure 8. *Example of MEMS Pressure Data as Compared to Wind Tunnel Data for the Smart Wing Test*

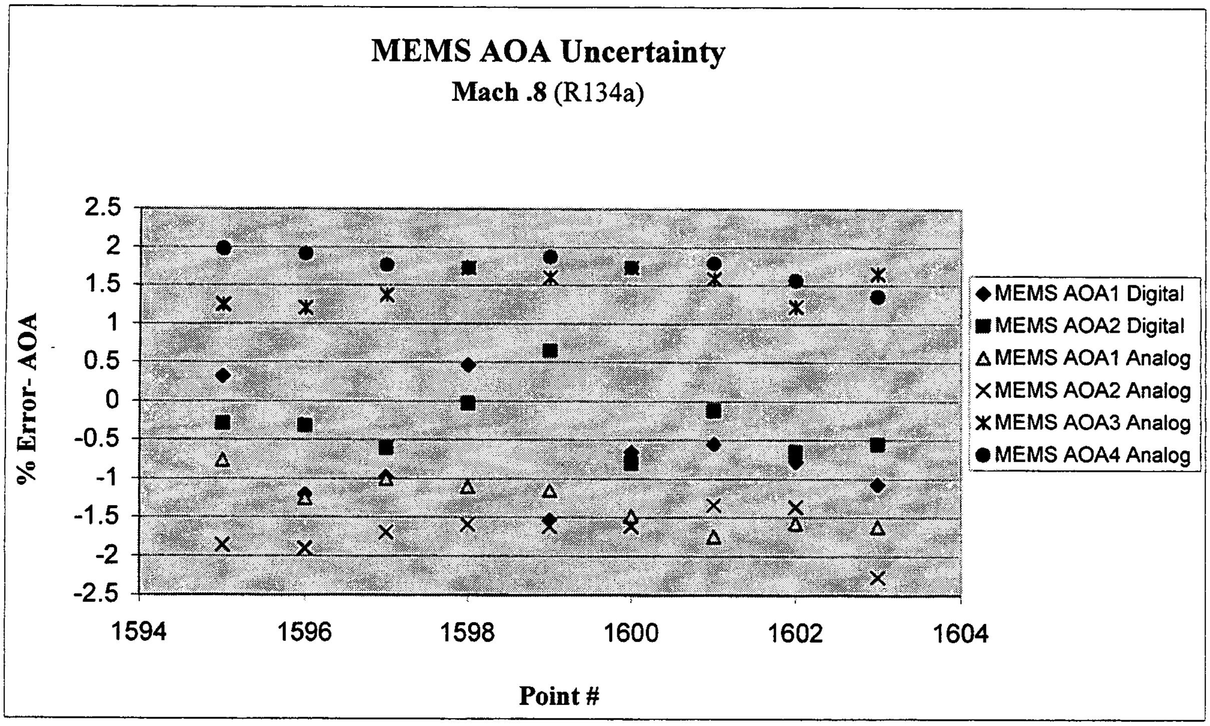

Figure 9. *Examples of MEMS AOA System Error for the Smart Wing Test*

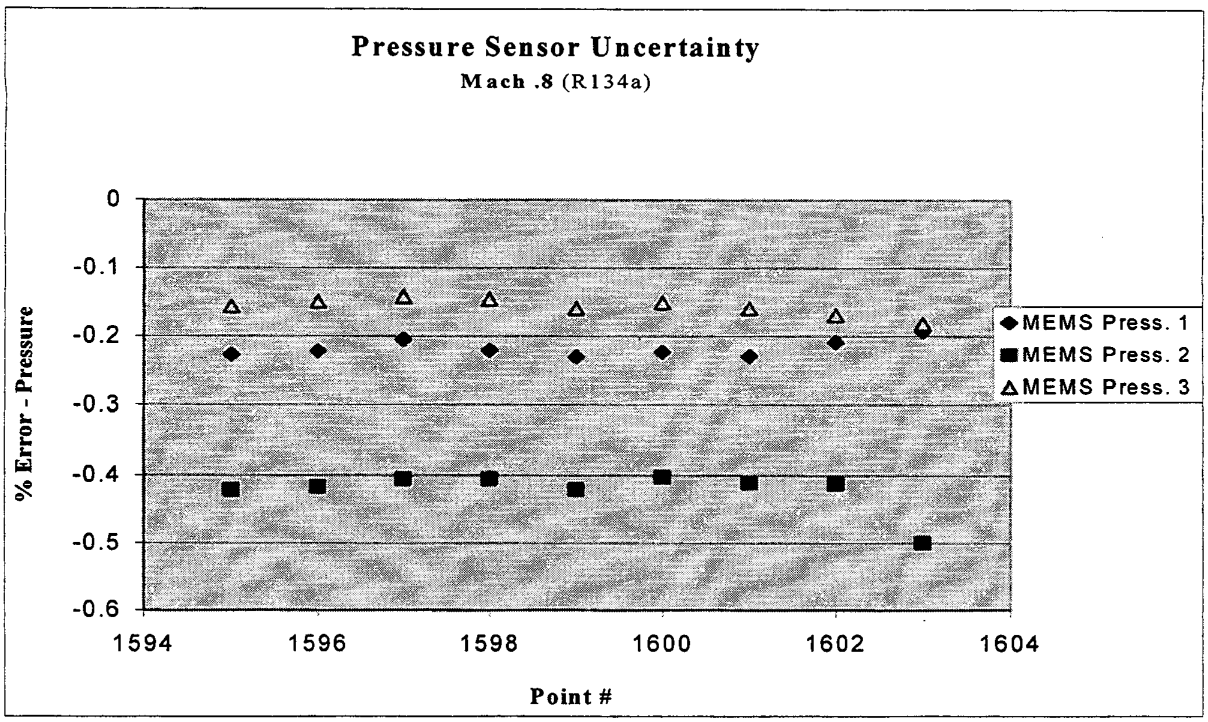

Figure 10. *Example of MEMS Pressure System Error for the Smart Wing Test*

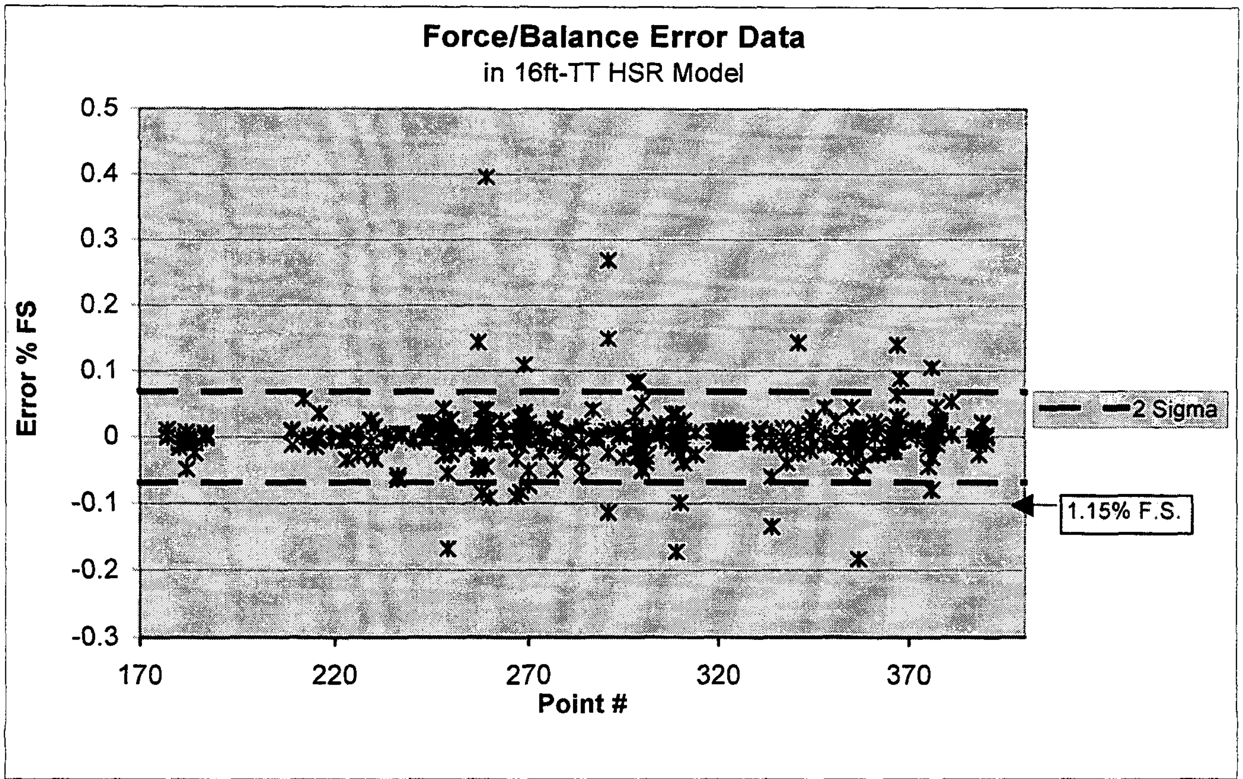

Figure 11. *Example of System Error in Model Force/Balance Data for the HSR Test*

CONCLUDING REMARKS

In conclusion, the advantages of an embedded system have been demonstrated and reasonable agreement was obtained when compared to the results from conventional data methods used in two wind tunnel tests. The system reliability and robustness have been shown with long term wind tunnel testing, subjected to a diversity of test conditions. The embedded system has shown no evidence of interference from or to, other tunnel or separately tested systems. The data collection and host computer is a standard laptop with a real-time graphical display of corrected engineering units. This system has been configured for autonomous operation, with no need for constant monitoring. With these results this system is well suited for a variety of wind tunnel measurements as well as an assortment of transducer inputs. Some of the general conclusions about the embedded, wireless DAS are:

Advantages

- Promotes "Plug and Play/Test" concept
- System flexibility, variety of signal inputs
- Small size promotes a large application base
- Reproduces tunnel data well
- Primary failure mode is RF signal dropout

Limitations

- Filtering techniques, more study needed
- Dynamic Range, need to increase
- Power budget, can be reduced

Setting these error areas to improve aside, the usefulness of an embedded DAS system that addresses some of the fundamental problems of the current state of wind tunnel DAS techniques, makes this a valuable effort that is worth further development.

Some of the future plans in this systems development include such items as, reducing the embedded electronics (DAS) size, improving sensor accuracy, increasing telemetry data transfer rate, increasing the number of data channels as well as battery powering for complete wireless applications, among others.

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