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Development of a Venus Surface Wind Sensor Based on a Miniature Drag-Force Anemometer

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Summary

To better understand the atmospheric structure and dynamics on the Venus surface and provide input to climate models, there is a need to measure the wind velocity and direction on the surface and track changes over extended periods. A wind sensor based on a miniature drag-force anemometer is being developed to meet the challenges for wind measurements and operational requirements on the surface of Venus. The sensor materials are chosen to enhance durability and prevent reactivity with the Venus surface atmosphere. Advantages of this approach include that it is independent on variable heat transfer, has been matured in other harsh environment applications, and has a low mass and power requirement. This report describes demonstration of this miniature drag-force anemometer integrated with high-temperature electronics in a simulated Venus surface environment. Prototype drag-force anemometers were demonstrated integrated with an operational amplifier recording transient effects in a simulated Venus surface environment. For multidirectional wind monitoring, the sensors are small enough to be deployed orthogonally as a three-dimensional array on a small arm or mast.

1.0 Introduction

The ability to measure the wind on the surface of Venus and track changes over a long time period is key to better understand the planet's atmospheric structure and dynamics (Ref. 1). Previous short-lived landers used cup anemometers (Venera 9 and 10), acoustic microphones (Venera 13 and 14), and radio Doppler shifts (Venera and Pioneer Venus missions) to estimate wind speed on descent and on the surface. Wind speed measurements on the planet's surface ranged from 0.35 to 1 m/s, averaging 0.6 m/s in the high-density atmosphere. However, uncertainties of these measurements were sizable, up to ±50 percent for Venera 14 (Ref. 2).

For long-duration Venus surface missions such as the Long-Lived In-Situ Solar System Explorer (LLISSE) (Ref. 3) or the Seismic and Atmospheric Exploration of Venus (SAEVe) (Ref. 4), the challenge is to develop wind-sensing technology to survive the harsh environments for long periods as well as have minimal impact to the power and mass budgets of the lander. Most traditional anemometry methods are not practical for long-term wind measurements on the surface of Venus. Mechanical or spinning anemometers are subject to dust and corrosion effects that would be significant on the Venus surface. Hot wires or films require significant power to further heat the already hot ambient Venus air. Doppler and acoustic anemometers require electronics that are not currently available for long-term use in the 465 °C environment of Venus.

For long-term use under low power and mass requirements, a miniature drag force anemometer is seen as a solution to meet the challenges for wind measurements on the surface of Venus. A drag-force anemometer allows use as an array without the dependence on a moving mechanical vane. This report discusses the approach, design, devices, and results of the development of a prototype miniature drag-force anemometer for use as a future Venus surface wind sensor.

2.0 Approach

A drag-force anemometer measures the bending deformation due to the force of a flow impinging on an extended cantilever beam using strain gauges. The strain gauges are placed on the beam near its bend point. The strain measured is proportional to the applied force on the cantilever, which is proportional to the square of the flow velocity with a given atmospheric density. To detect changes in flow direction, multiple beams are used in different orientations. The miniature drag-force sensor design is applicable to both a steady-state and turbulent flow.

The miniature drag-force anemometer design for turbine engines was first outlined by Krauss and Fralick in 1977 (Ref. 5). The anemometer has since been tested and validated in multiple ground-based studies: in tests on turbofan engine inlet and bypass duct using several different configurations (Refs. 6 and 7), in supersonic flow tests (Ref. 8), and at 600 °C in the hot section of a turbine engine (Ref. 9). The turbofan tests and the supersonic flow tests utilized sensors fabricated with metal and silicon cantilever beams using foil and semiconductor strain gauges. The hot section turbine flow tests utilized sensors fabricated with 6H-SiC cantilever beams with piezoresistive strain gauges.

Though the approach was demonstrated in aeronautic applications, the drag-force anemometers fabricated in these studies used material that would not survive in the harsh Venus surface environment. For Venus surface applications, cantilever beam and strain gauge materials were chosen to prevent reactivity with the corrosive atmosphere (Ref. 10). Alumina and sapphire (single crystal alumina) were selected as the cantilever beam material, gold film for the strain gauge, and stainless steel for the supporting structure. A Venus anemometer was designed using these materials, with the latest prototype shown in Figure 1 and described here.

3.0 Design

For meaningful science on the Venus surface, the goal is to measure wind velocities in the range of 0.25 to 2.5 m/s, ±0.1 m/s, as well as wind direction over an extended period of time with minimal impact on the power and mass budget of the lander (Ref. 3). For this application, the sensor must be operational for at least 60 days at 465 °C in a high-pressure CO_2 supercritical atmosphere with a density of 67 kg/m^3, including chemically reactive species such as SO_2. The sensor must also be low power (less than 10 mW) and low mass (less than 1 kg).

To meet these criteria, the design is based on the approach by Krauss and Fralick (Ref. 5), as outlined in Figure 2. The stress σ on the beam impinged on by a flow with a drag force D is

$$\sigma = E\varepsilon = \frac{6T}{wt^2} \tag{1}$$

where E is the Young's modulus, ε is strain, T is moment, w is width, and t is thickness of the beam.

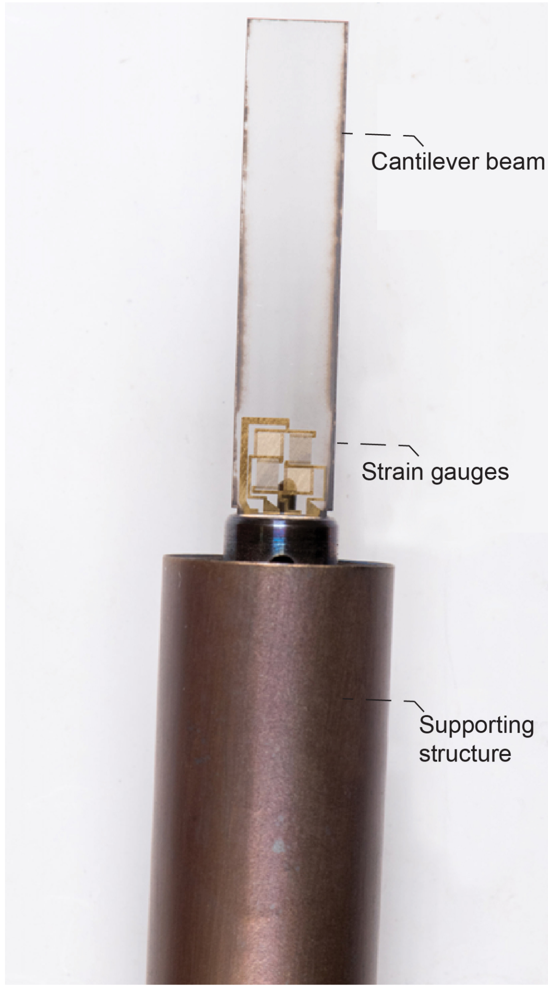

Figure 1.—Prototype miniature drag-force anemometer for use as future Venus surface wind sensor. Cantilever beam is 8.4 mm in width.

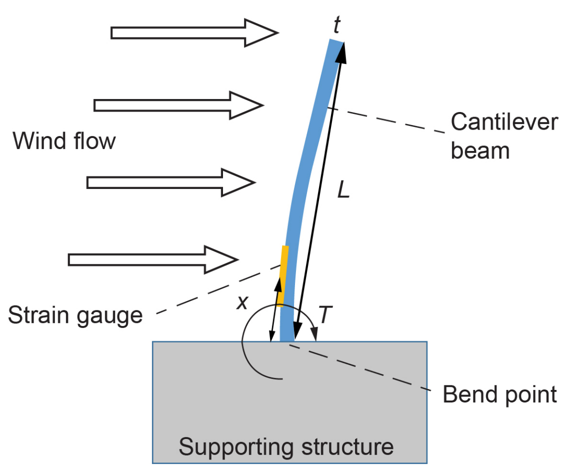

Figure 2.—Strain analysis on drag-force anemometer cantilever.

The moment is found from D:

$$D = \frac{\partial T}{\partial l} = \frac{1}{2} C_d \rho l w U^2 \tag{2}$$

where C_d is the drag coefficient, U is wind velocity, l is distance along the beam where the moment is determined and ρ is flow density. Integrating l in Equation (2) along the total length of the beam L:

$$T = \frac{1}{4} C_d \rho w U^2 L^2 \tag{3}$$

Thus, the maximum stress on the beam due to the wind is

$$\sigma = \frac{3}{2} C_d \rho U^2 \frac{L^2}{t^2} \tag{4}$$

To determine strain at the strain gauge, the moment where the strain gauge is located (at x) is determined:

$$T(x) = \frac{1}{4} C_d \rho w U^2 \frac{L^2 - x^2}{2} \tag{5}$$

Thus, the stress at the strain gauge is

$$\sigma(x) = \frac{3}{4} C_d \rho U^2 \frac{L^2 - x^2}{t^2} \tag{6}$$

The measured strain is thus:

$$\varepsilon(x) = \frac{\sigma(x)}{E} = \frac{3}{4} C_d \rho U^2 \frac{L^2 - x^2}{E t^2} \tag{7}$$

Note that the strain in Equation (7) is not dependent on the beam width, but it is dependent on the square of wind velocity, fluid density, and beam length and thickness. Thus, for a specific cantilever geometry, the velocity is directly determined by the strain measurement:

$$U = \left[\varepsilon(x) E \frac{t^2}{\frac{3}{4} C_d \rho \left(L^2 - x^2 \right)} \right]^{1/2} \tag{8}$$

For the physical dimensions of the sensor in this application, the cantilever beam is sized to fit within a 100-mm-diameter commercially available alumina or sapphire wafer. To fit within such a wafer with allowance for edge effects, beams are set to 63 mm of total length. The length for attaching lead wires to the gauge is set at 23 mm long to allow adequate working space, leaving a cantilever beam length (L) of 40 mm exposed to the drag force of the wind flow (see Figure 1).

The width of the cantilever described and evaluated in this report is defined by an inside tube diameter of the pressure feedthrough for the testing facility (discussed in the following sections). The beam width (w) of 8.4 mm is set to allow enough clearance of the cantilever to be inserted into the feedthrough without breaking.

On the Venus surface, the atmospheric density (ρ) is 67 kg/m³ with a maximum expected wind velocity (U) of 2.5 m/s (Ref. 3). The drag coefficient (C_d) can be estimated at 1.22, multiplied by the cosine of the incident angle of the drag force (D) (Ref. 6). A minimum wafer thickness (t) of 127 µm gives an expected maximum stress of 76 MPa under these conditions using Equation (4), well below the 480 MPa failure rating of sapphire (Ref. 11). Based on these calculations, the beam is expected to be operational in the flow range of interest, experiencing 1 µm/m of strain in a 0.25 m/s breeze, but potentially fail in unlikely extreme 6.3 m/s wind gusts on the Venus surface.

As noted earlier, the strain gauges themselves are selected to be thin films of patterned gold. To measure the strain, changes to the resistance of the gauges (R) are measured, preferably in a full Wheatstone bridge configuration. The fractional amount of change of resistance to applied strain is proportional to a gauge factor (G_f):

$$\frac{dR}{R} = G_f\,\varepsilon(x) \tag{9}$$

To document the functionality of gold as a strain gauge at high temperatures, a gold film of thickness 0.7 µm was sputtered and patterned on a constant strain beam made of 99.6 percent pure hot-pressed alumina and tested to determine gauge factor and temperature coefficient of resistance (TCR) to 465 °C in air. Not only did the gauge function, but the gauge factor (4.5 at room temperature) was found to increase at high temperature and change sign to –35 (±22 percent). The TCR of the gold film was found to be 2,400 ppm/°C, less than the bulk value of 4,000 ppm/°C (Ref. 12). Thus, with a gauge factor of –35 and a minimum strain of 1 µm/m, from Equation (9) the lower bound of the fractional resistance change is 35 µΩ/Ω. Though the fractional resistance change is directly measured in a full-bridge configuration, a gold strain gauge with, for example, a 70 Ω resistance will give a 0.5 mΩ resistance change with a 1 µm/m strain. The low TCR and high gauge factor at 465 °C implies that the gold film is suitable as a strain gauge material for producing drag-force anemometers for use as Venus surface wind sensors.

4.0 Sensor Fabrication

A prototype wind sensor composed of both a sensor and conditioning electronics chip was produced using strain gauges fabricated with the previously described design approach and integrated with a silicon carbide-based operational amplifier produced in-house ("Gen10" differential mode amplifier) (Refs. 13 and 14). This prototype is the first embodiment of a wind sensor with integrated amplification electronics as envisioned for Venus surface operations. This report concentrates on the development of this prototype wind sensor; previous unpublished work also occurred validating the concepts in simulated Venus surface conditions (VSC) to result in this prototype design but will not be described herein.

A schematic of the prototype wind sensor is outlined in Figure 3. The integrated sensor and electronics system is designed to be placed in the ¾-in.-diameter stainless steel tube feedthrough for testing in simulated VSC in the Glenn Extreme Environments Rig (GEER) chamber (Ref. 15). The fabrication of the SiC integrated circuit (IC) electronics is described elsewhere (Ref. 14). In the following, the fabrication of the sensor gauge, integration with the SiC amplifier electronics, and implementation in the GEER chamber are described.

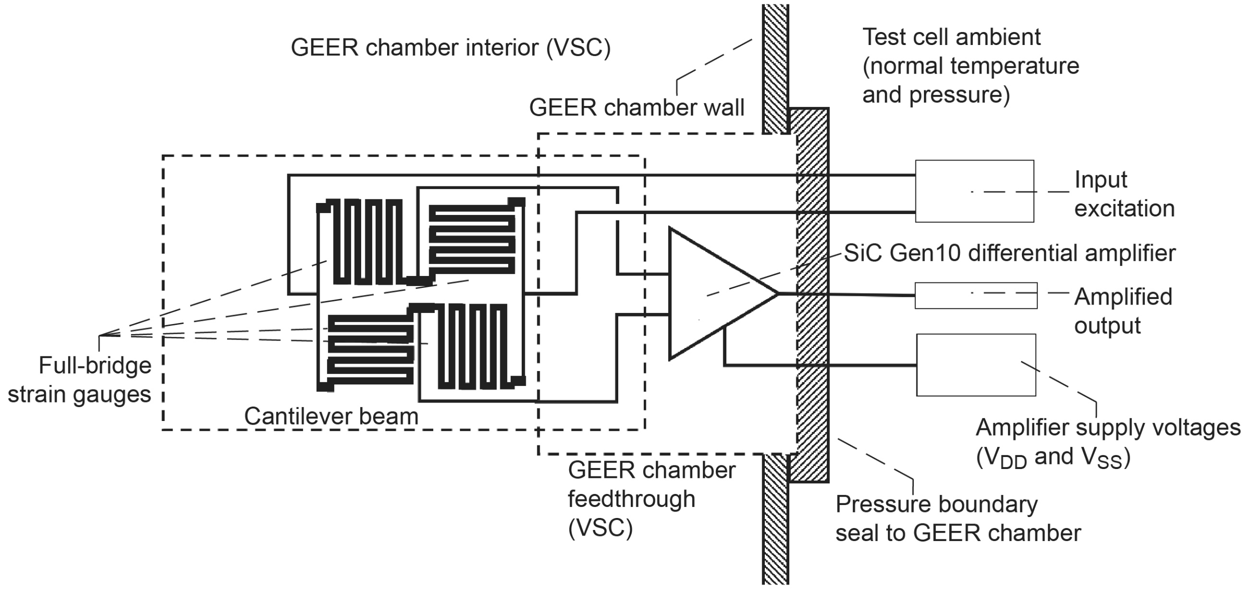

Figure 3.—Prototype Venus wind sensor. A cantilever beam with full-bridge strain gauges is mounted into Glenn Extreme Environments Rig (GEER) chamber feedthrough that contains SiC Gen10 differential amplifier. Power supplies and data acquisition system reside outside of chamber. Venus surface conditions (VSC). Drain supply voltage (V_{DD}). Source supply voltage (V_{SS}).

The cantilever beams were fabricated from 127-µm-thick commercial sapphire wafers. To form the strain gauge on the beam, the sapphire wafer was first coated with gold film using a titanium bond coat by sputtering in argon in a single run (not breaking vacuum). A lithographic pattern was then formed on the film with photoresist, and the uncovered metal film was etched away using aqua regia. The photoresist was removed with acetone leaving the gold pattern, which was then annealed at 600 °C for 8 h in air using a box furnace. Due to the microscopic voids in the sapphire wafer surface, a gold film of approximately 1 µm with a 50-nm titanium bond coat was found to be the ideal thickness to survive the annealing cycle. After annealing, the cantilevers were laser cut from the sapphire wafer.

A cantilever mount, whose design is shown in Figure 4, was custom made in-house from 316 stainless steel to hold the beam in the ¾-in.-outside-diameter feedthrough for the test. The cantilever mount was fastened to the feedthrough tube using welded metal straps. Gold wires of 0.010 in. diameter were attached to the cantilever beam with conductive paste, and then spot welded to the feedthrough wires. A type K thermocouple (TC) probe (0.0625-in.-diameter sheath, 316 stainless steel, ungrounded) was fixed in the cantilever mount below the beam to measure local gas temperature.

The cantilever beams have strain gauges in a full-bridge configuration patterned on one side, shown in Figure 5 (and seen as well as in Figure 1 and Figure 6). Each strain gauge bridge arm has a line width of 30 µm and l/w of 1,869, centered 3.9 mm from the bend point (the distance “x” in Figure 2 and Eqs. (5) to (8)). The Gen10 operational amplifier was wired in an open-loop configuration to operate the full-bridge configuration. The amplifier gain previously was measured at simulated VSC in a GEER run as ×35.6 (±2.2%) under drain supply voltage (V_{DD}) of 25 V and source supply voltage (V_{SS}) of –25 V. The prototype wind sensor is placed in the tip of the feedthrough probe with the operational amplifier. The wires from the sensor’s strain gauges and the amplifier are fed through the body of the probe. The completed assembly of the prototype wind sensor into a feedthrough probe structure for insertion in the GEER chamber is shown in Figure 6.

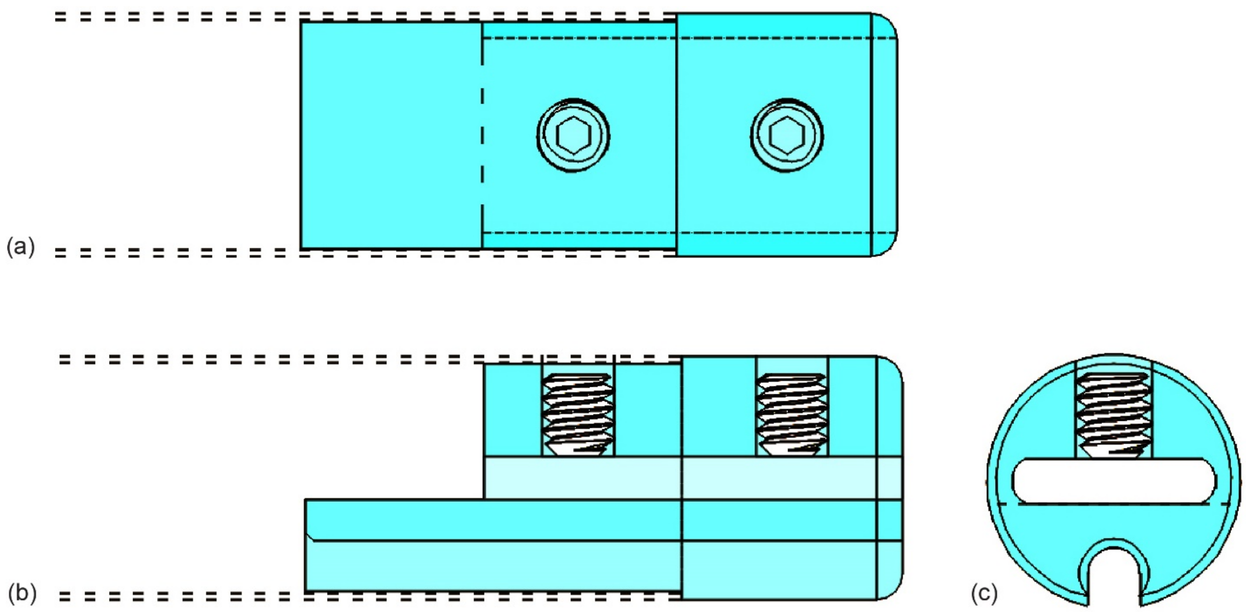

Figure 4.—Cantilever mount design attaching to end of ¾-in.-outer-diameter stainless steel tube. Cantilever is inserted into slot in center held in place with spacers and set screws. Thermocouple sits in notch at bottom of (c). (a) Top view. (b) Side view. (c) End view.

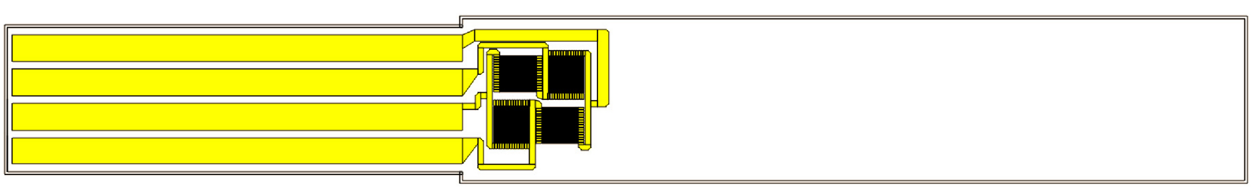

Figure 5.—Photolithography mask pattern for cantilever.

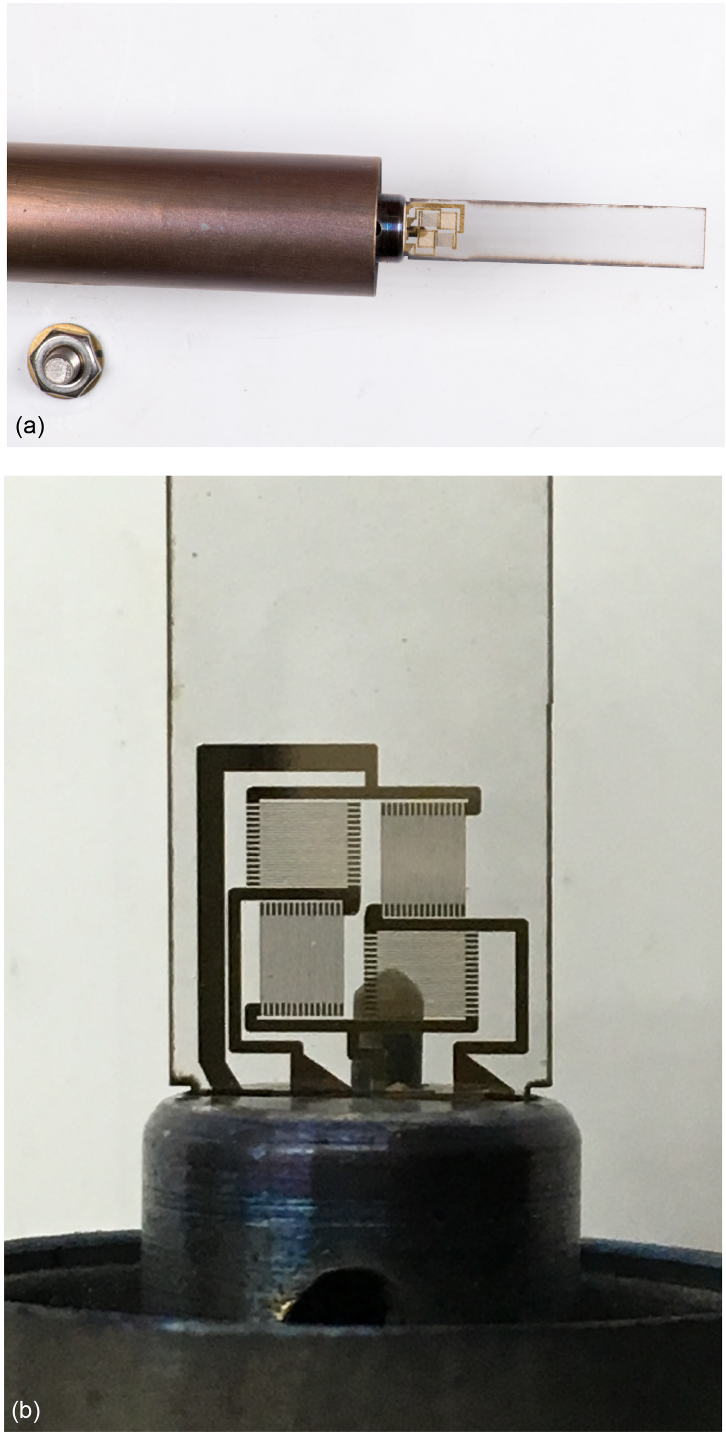

Figure 6.—Prototype sensor assembly showing (a) cantilever and strain gauges and (b) closeup of strain gauge full bridge. The cantilever width is 8.4 mm.

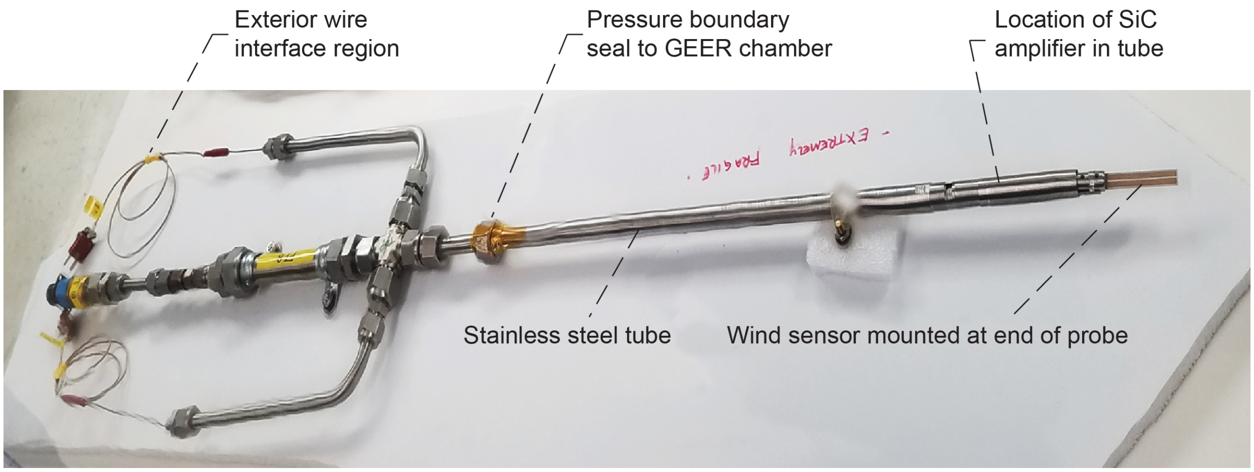

Figure 7.—An earlier prototype wind sensor feedthrough probe showing general components. Glenn Extreme Environments Rig (GEER).

The general feedthrough probe structure for insertion in the GEER chamber is shown in Figure 7 and includes

- The exterior wire interface region where wires from wind sensor in the interior of GEER join to the exterior wire connections
- The pressure boundary seal where the probe is fastened to the GEER chamber fitting
- Seamless ¾-in.-outside-diameter 316 stainless steel tube housing the wires connecting to the SiC amplifier and wind sensor inside of the probe
- Wind sensor mounted at end of the probe and exposed to the chamber environment

The feedthrough probe is inserted into a ¾-in. stainless steel fitting on the GEER stationary flange. Figure 8 shows the implementation of the wind sensor installed into GEER (a) from inside as it protrudes into the chamber and (b) from the outside looking at the fitting in which it is mounted in the GEER stationary flange. The feedthrough extends approximately 10 in. into the chamber, located directly opposite of the inlet port used for adding gas into the GEER chamber during operations.

For testing, the wind sensor was positioned in the GEER chamber with the cantilever beam face oriented parallel to the cylindrical chamber wall, as shown in Figure 8, in order to be the most sensitive to convection currents in the chamber. Other articles under test in the chamber could cause some variability of the immediate environment in the vicinity of the wind sensor. Overall, the implementation of the wind sensor is intended to allow monitoring of gas insertion into the GEER during simulated operation in VSC, as well as during heating and cooling transition periods.

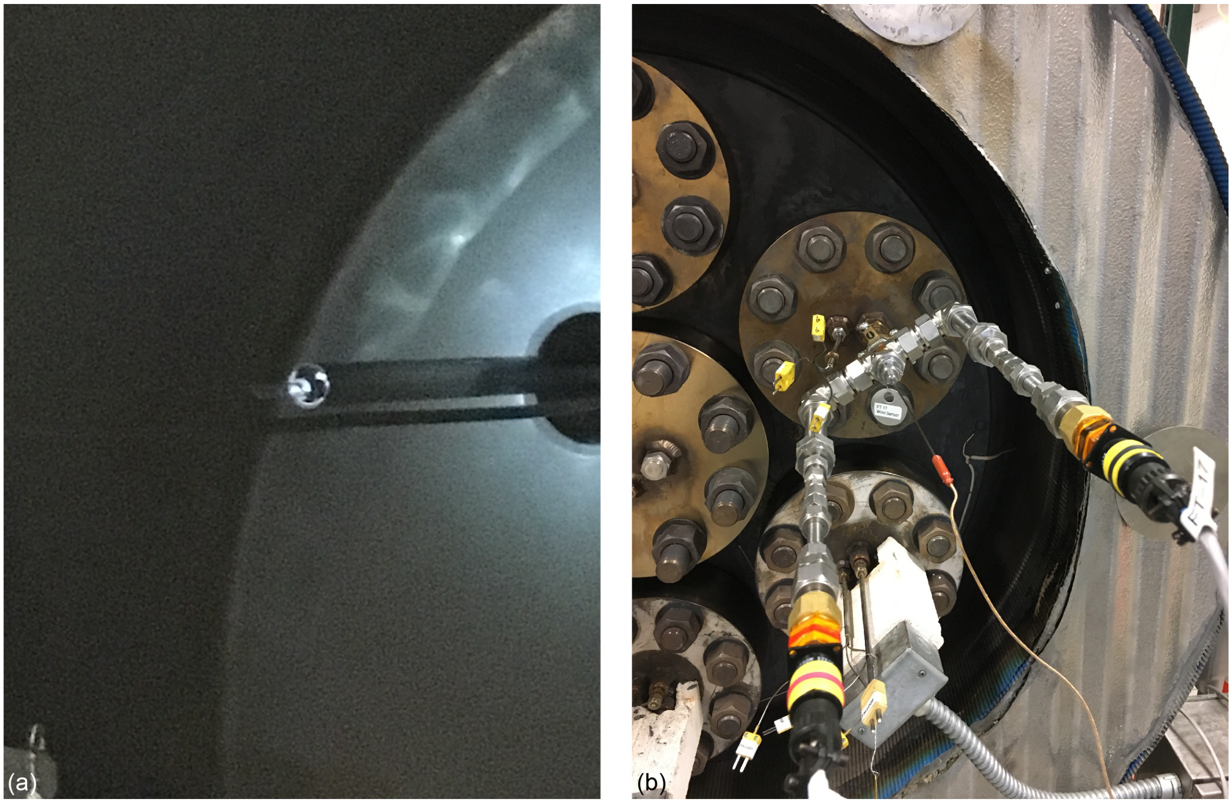

Figure 8.—Wind sensor prototype installed in Glenn Extreme Environments Rig (GEER) prior to run viewed (a) inside chamber and (b) outside chamber. Sensor was installed similarly for each run.

5.0 Results

Prototypes of the miniature drag-force anemometer as a Venus surface wind sensor were demonstrated in the GEER facility under VSC after implementation as described previously. Prototype sensors were tested in two runs, denoted as the GEER “RFPT” and “LFT1” runs. The RFPT test lasted a total of 34 days and had test conditions varying from VSC up to approximately 55 km elevation including ascent and descent. The LFT1 test occurred over a total of 23 days at VSC.

The test results in the following sections demonstrate the ability of the prototype wind sensor to respond to changing conditions at VSC, as well as reflect the ability of the sensor to, in general, respond to changing conditions in the chamber.

5.1 RFPT Results

The wind sensor for the RFPT run was operated in a full-bridge configuration as described previously with a bridge input resistance at room temperature of 38 Ω and a gold film thickness of approximately 1.9 µm operated with an input excitation voltage of 1 V. The amplifier supply voltages were set to V_{DD} = 25 V and V_{SS} = –25 V. Data was recorded every 2 s continuously during the run using a computer-controlled data acquisition system.[1]

[1]Data acquisition performed using a National Instruments Corporation platform operated by a custom LabVIEW program.

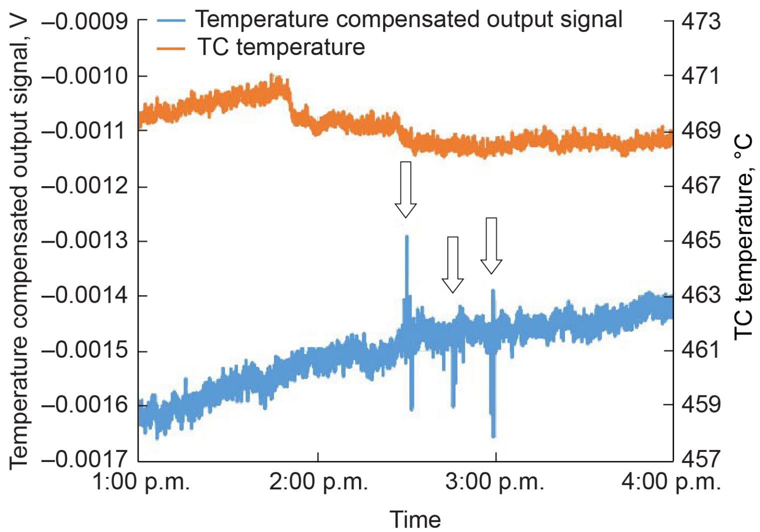

Figure 9.—Output at beginning of Venus surface conditions during RFPT run showing reaction to gas boosts indicated by arrows and unrelated to temperature. Thermocouple (TC).

The run began with a system ramp up to 500 °C under vacuum over a period of 155 h. The amplified signal was initially observed to fluctuate irregularly as much as ±88 µV, which stabilized after 150 h of "burn-in" from the start of the ramp. Since data from the amplifier output during the ramp was taken under vacuum, the signal was solely dependent on temperature and included the temperature dependence of the zero-velocity bridge offset combined with the operational amplifier. A 45.2 µV/°C temperature dependence was determined from the vacuum data at 488 °C, and this value was used for temperature compensating the data from the test.

After the initial burn-in, the signal showed an overall ripple of approximately ±16 µV in the amplified signal for the remainder of the run. At the beginning of the VSC portion of the test, three spikes of 0.18 mV that corresponded with gas boosts injected into the GEER chamber are seen in the temperature-compensated signal as shown in Figure 9. During these gas boosts and signal spikes, there are no corresponding changes in the measured TC temperature, supporting the conclusion that the wind sensor is responding to changes in the flow of the chamber and not the ambient temperature.

5.2 LFT1 Results

After the RFPT run, the cantilever beam was replaced by a beam with higher resistance strain gauges towards attaining lower power consumption target of less than 10 mW desired in the design criteria. The modified wind sensor for the LFT1 run was also operated in a full-bridge configuration as described previously with a room-temperature bridge input resistance of 65.3 Ω and gold film thickness of approximately 1.1 µm operated with an input excitation voltage of 1 V. As previously, the amplifier supply voltages were set to $V_{DD} = 25$ V and $V_{SS} = –25$ V. Data was recorded every 2 s continuously during the run using the computer-controlled data acquisition system as described previously.

During the initial warmup in the test, the wind sensor signal was very unstable, but recovered after the GEER temperature had increased over 350 °C in the simulated Venus atmospheric environment. This signal remained stable for the rest of the test, including during operations and subsequent cooldown.

Based on the cooldown of the pressurized vessel after the test, a temperature response of –90 µV/°C was observed for temperatures over 400 °C, opposite in sign and double that of the previous test. A ripple of approximately ±82 μV was seen in the amplified signal at VSC for temperatures over 380 °C, 5 times of that seen in the previous test. As the temperature reduced during cooldown, the noise reduced to ±40 μV at 40 °C. This implies an increased noise and temperature sensitivity of the overall prototype sensor is unlikely to be solely due to changes in film thickness. Based upon unpublished microscopic observations[2] of modifications on a different SiC IC that was run multiple times in VSC but exposed to Earth air in between runs, we suggest it is plausible that similar inadvertent modifications of this operational amplifier may have occurred between the two runs.

The wind sensor also registered gas injection boosts not associated with thermal affects seen by the TC. An example of changes in the wind sensor response corresponding to gas boosts into GEER is shown in Figure 10. Variations in the signal immediately after the gas boost correspond to expected oscillations in the GEER environment associated with the gas boost. As seen in Figure 10, the changes in the wind sensor response are not associated with corresponding changes in the measured TC temperature. This lack of correlation between temperature changes and sensor response implies that the change in signal from the wind sensor reflects tracking changes in gas flow in the chamber and is not due to temperature changes affecting the sensor or amplifier. The wind sensor signal shown in Figure 10 does recover to near the original baseline over time after the gas boost. This type of effect was seen multiple times with each gas injection boost.

This type of change in the wind sensor response to gas boosts into GEER without an equivalent change in temperature was seen multiple times and suggest the ability of the wind sensor to track gas boosts into the GEER chamber throughout the LFT1 run. A –5 mV change in signal output was consistently generated with each gas boost.

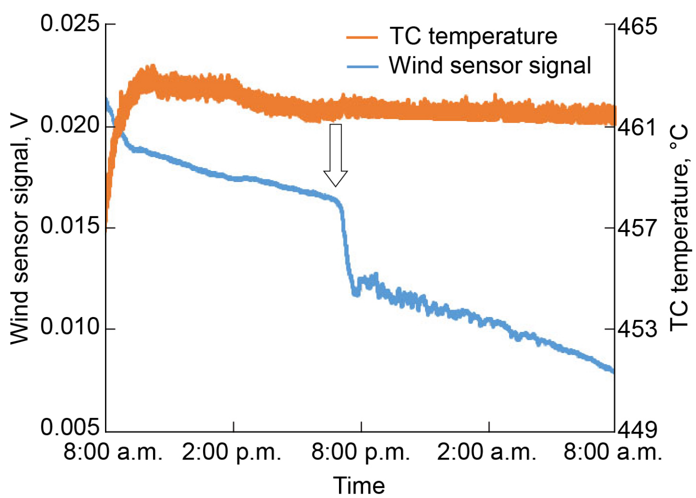

Figure 10.—Response of wind sensor signal (blue trace) to a gas boost to Glenn Extreme Environments Rig (GEER) at time indicated by arrow during LFT1 run, without corresponding change in temperature measured by thermocouple (TC) (orange trace).

[2]Neudeck, P.: Personal communication, Aug. 17, 2020.

TABLE I.—SUMMARY OF ANEMOMETER PROTOTYPE OPERATIONAL CHARACTERISTICS

GEER run	RFPT	LFT1
Input resistance at 20 °C, Ω	37.9	65.3
Input resistance at Venus surface conditions (VSC), Ω	76.9	154
Power consumption at VSC (excluding amplifier), mW	13	6.5
Output ripple noise at VSC, mV	±0.016	±0.082
Maximum event signal, mV	0.18	5
Maximum signal-to-noise	11	61
Maximum strain, μm/m	0.14	4.0
Maximum estimated gust at VSC, m/s	0.094 ± 0.011	0.495 ± 0.055

5.3 Summary of Results

A summary of the operational characteristics of the prototype sensors demonstrated in the GEER facility at VSC is given in Table I, along with the equivalent gust velocity calculated from Equation (8) of the maximum event signals seen during their respective runs.

Using the amplifier gain and gauge factor previously measured at VSC temperature, the estimated maximum gusts correspond to 0.094 and 0.495 m/s in the two runs, with ±0.010 and ±0.053 m/s uncertainties, respectfully. These values are within a lower range of wind velocities observed by Venera landers on the Venus surface. The maximum gusts correlated with gas boosts in the GEER chamber without corresponding temperature fluctuations recorded on the embedded TC.

The uncertainties of the velocity readings of the sensors are dominated by the uncertainty in the gauge factor. The second iteration of the drag-force anemometer showed an improvement in signal-to-noise when boosts were registered.

6.0 Conclusions

NASA Glenn Research Center is developing a drag-force anemometer for use as a Venus surface wind sensor. The sensor uses technology proven in turbine-based applications and is designed for long-term stable operation in the Venus surface environment. Prototype drag-force anemometers were demonstrated with an integrated operational amplifier in Venus surface conditions (VSC), recording transient effects time correlated to gas injection boosts in the GEER chamber. These prototype sensors are medium-fidelity systems built and operated to demonstrate overall performance in a simulated operational environment.

Though the location of the wind sensors in the chamber were consistent for each run, the GEER chamber environment had some variation based on the articles under test inside the chamber and the actual run conditions. These variations led to changeability in the maximum wind gusts recorded by the sensors. To our knowledge, these results are the first demonstration of a wind sensor integrated with electronics operating in situ in simulated VSC.

Future versions of the sensor design will include trim areas to produce sensors with strain gauges with more consistent resistances to further minimize variable temperature effects on the signal at VSC and maximize the overall sensitivity and output. Likewise, improvements in amplifier circuit characteristics are also expected in future generations of SiC amplifier integrated circuits.

Operating the sensors in an array is the goal of the project for implementation on the Venus surface, and final configuration is yet to be established. The current concept is of a mast with three cantilever beams for x, y, and z sensitivity, each with their own operational amplifier. The results presented here suggest the strong viability of this concept towards reaching the goal of achieving long-term wind measurements on the Venus surface.

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