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Design Requirements and Static Performance Analysis of a Strain Gauge Anemometer

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Abstract – **This paper describes the operation principle, design requirements, and static performance analysis of the anemometric device based on strain gauge sensors. It also includes examination of the effect that environmental variables (air density, humidity, and atmospheric pressure) have over the measurement results.**

Keywords – **Strain Gauge Anemometer, Wind Direction, Wind Speed, Weather Station.**

I. Introduction

As an evaluation of the Adaptive Weather Station project, was set a requirement to develop anemometric system for work in extreme conditions.

Wind characteristics are typical example for environmental parameters that could require both long-term and real-time measurements. Tracking the wind speed and direction changes is specific and important task not only for the matter of weather and climate study, but also for a various everyday activities. In cases where conventional anemometers are not applicable, this task could be very challenging. Examples of such cases are places where wide temperature deviation exists and could cause freezing of the moving parts of the anemometer or blocking them due to infestation of small particles from dust and/or ice.

This task requires development of low-power anemometer without moving parts. Additionally, it should be able to communicate with external systems and provide data on-demand and as per the requirements of the real-time operation.

Due to the above constrains, an idea for strain gauge anemometer has appeared. This concept is unexplored solution for the problem and requires extensive research.

The design of strain gauge anemometric system is presented in additional paper, and another one presents the specifics in realization of the initial prototype and the proof of concept.

Purpose of the current paper is to present the analysis of the prototype characteristics and to outline the development of enhanced system with more proficient specifications.

II. Operation and Requirements

A. Operation Principle

For the purpose of the study, we can define the wind as a viscous fluid flowing through a rigid solid with a certain speed and direction. Therefore, the fluid will act on the body with aerodynamic force, the size of which depends on the shape of the body and the velocity of the fluid.

The aerodynamic force is commonly resolved into two components – drag and lift force. With certain precautions, as described below and in previous papers, the body shape could be selected so as to neglect the lift force and to be affected only by the drag force.

Drag force is defined as shown in equation (1), where C is drag coefficient, ρ is the density of the air, S is the cross sectional area, and v is the speed of the object relative to the fluid.

$$\vec{F} = \frac{1}{2} C\rho S\vec{v}^2 \tag{1}$$

Therefore, by measuring the drag force caused by the wind over the body, determination of both wind speed and direction could be done via equation (2).

$$\vec{v} = \sqrt{\frac{2\vec{F}}{C\rho S}} \tag{2}$$

From this perspective, there are two components that require additional review – anemometer's body shape and density of the air.

Anemometer's body shape profile (drag coefficient and cross sectional area) needs to be known for each measurement direction. For simplification, surface wind will be considered mainly as a two-dimensional vector [1]. This assumption allows us to use simple body shapes with equal profile parameters on all wind directions, thus simplifying the calculations.

Air density is a parameter that varies with changes in temperature, pressure, and humidity [2]. The density of dry air can be calculated using the ideal gas law, expressed as a function of temperature and pressure. To include also the effect of humidity, the density of humid air may be then calculated by treating it as a mixture of ideal gases, as shown on equation (3).

$$\rho = \frac{p_a M_a + p_v M_v}{RT} \tag{3}$$

Where M_a is the molar mass of dry air, and M_v is the molar mass of water vapor (both constants). R is the universal gas constant, and T is the absolute temperature. In this case, the absolute pressure p is considered the sum of partial pressures of the dry air (p_a) and vapor pressure

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(p_v), where vapor pressure is directly derived by saturation vapor pressure (p_{sat}) and relative humidity (U). Recommended way to calculate the saturated vapor pressure is via modification of Magnus' formula [1] (t is temperature in °C), as shown in equation (4).

$$p_{sat} = 611.2e^{\frac{17.62t}{237.8+t}} \quad (4)$$

Using this method, error in the saturated vapor pressure calculation, compared to reference data [2], is less than ±0.3%.

The air density is then transformed to equation (5).

$$\rho = \frac{pM_a + Up_{sat}(M_v - M_a)}{RT} \quad (5)$$

Therefore the wind speed equation could be transformed in equation (6).

$$\vec{v} = \sqrt{\frac{2\vec{F}RT}{CS(pM_a + Up_{sat}(M_v - M_a))}} \quad (6)$$

This modification allows us to determinate wind speed by directly measure all variables.

B. Design Requirements

Operational principle requires the wind-measuring system to be able to measure the aerodynamic force, temperature, pressure, and humidity.

In addition, there are some performances requirements for wind measurements used in meteorology and climatology [1], shown in table 1, that are used as design reference.

TABLE 1. MEASUREMENT REQUIREMENTS

Parameter	Range	Resolution	Uncertainty
Wind Speed	0 – 75 m/s	0.5 m/s	0.5 m/s
Gusts	0.1 – 150 m/s	0.1 m/s	0.5 m/s
Wind Direction	0° – 360°	1°	5°

Sensing temperature, pressure, and humidity are not topics for this paper, but some additional information on those items can be found in papers for Adaptive Weather Station project.

For sensing aerodynamic force in the current project are used strain gauges. Strain gages, also referred as load cells, are sensors whose resistance varies with applied force - it converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured.

Specifics in the design of the load cells make them sensitive only in one axis, which in order to detect wind direction from 360 degrees, requires usage of two mounted with their sensing axes perpendicular. This method actually resolves the drag force into two components – F_x and F_y, each of which is measured by different load cell. The size and direction of the actual drag force is then determined trigonometrically.

The body shape profile of the load cells is not equal in all measuring directions, which requires additional element – covering coat. Covering coat is designed to transfer wind force to load cells evenly despite of the wind direction. It also serves to shields the sensors from the environment.

Final component of the structure is a main pivot, which serves as mounting rod for the entire construction. Structural design of the strain gauge sensor is shown on figure 1.

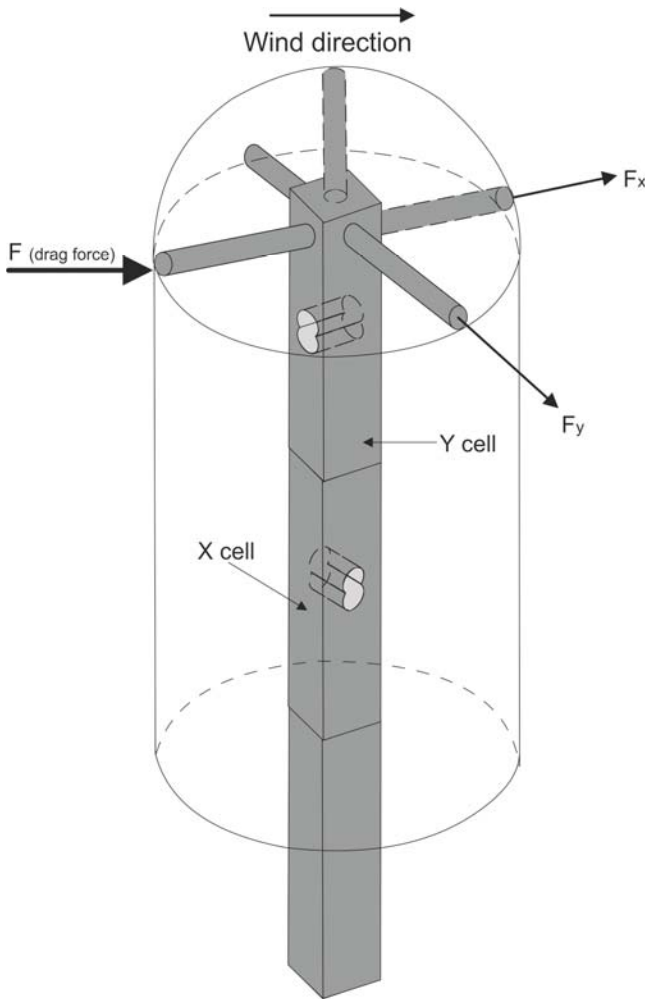

Figure 1 – Model of Strain Gauge Sensor

As stated above, the body shape profile is defined by covering coat characteristics. In the initial prototype it is built from a 20-cm aluminum tube with 24 mm diameter. The expected drag coefficient [4] is around 1.2, and cross section area is 0.0048 m^2. Size of the tube is selected in accordance with typical size for the load cells, so to cover them completely.

Based on these parameters, and assuming air density of 1.225 kg/m^3, the maximum drag force applied over the system would be 19.845 N for wind speed of 75 m/s. Therefore, for effective measurement of the maximum wind speed, the load cells should have full scale of 2 kg.

It is important to note, that as the force is quadratic function of velocity, doubling the velocity will actually quadruple the force. Ultimate overload rate of the load cell is usually 200% of the full scale, which means gusts over 105 m/s could damage the sensor.

C. Front-End Design

The front-end module is designed with two identical channels for sensing both load cells. Each channel consists of input low pass filtering system and instrumentation amplifier, as shown on figure 2.

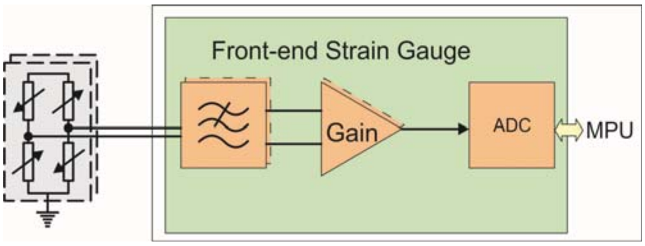

Figure 2 – Front-End Block Diagram

Each load cell consists of four 1-kΩ strain gauges in a full-bridge configuration. The rated electrical signal output is 1.0±0.15 mV/V, thus requires amplification by an instrumentation amplifier before it can be used.

Major issue of resistive bridge configuration is the stability of the supply voltage, as the output of any bridge is directly proportional to it. The circuit must either hold the supply voltage constant to the same accuracy as the desired measurement, or it must compensate for changes in the supply voltage. The simplest way to compensate for supply-voltage changes is to derive the ADC's reference voltage from the bridge's supply voltage.

Another specific requirement of the load cell is to work in both directions of force appliance. To allow working in this mode with a single-supply source is necessary to offset the output signal of the amplifier to a precise mid-supply level. This is done via applying voltage on the reference pin of the amplifier. Offset schema allows precise trimming and provide low impedance at the reference terminal to preserve good common-mode rejection. Schematic diagram of this configuration is shown on figure 3.

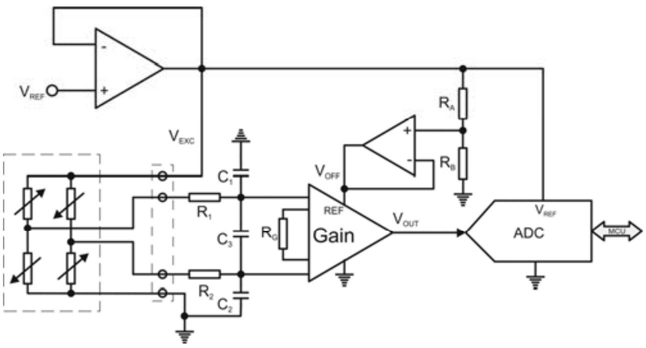

Figure 3 – Front-End Schematic Diagram

The amplification of the signal is done using precise instrumentational amplifier designed to work with strain gauges. Considering the requirements of the Adaptive Weather Station for a single 3.7-V battery supply and the rated output of the load cells mentioned above, load cell will provide 3.7-mV signal at full scale in each direction, or total of 7.4 mV. Which means that in order to not exceed the ADC's reference voltage, the maximum amplification of the signal should not be larger than 500 (it is 490 for the test configuration).

III. Parameter Analysis

Initial prototype uses 12-bit SAR ADC, which means that the voltage equivalent of 1 LSB is 0.9 mV. Therefore, for 2-kg load cell, the signal level corresponding to 1 LSB is 1.84 µV or 9.8 mN, which means that the lower threshold is at wind speed of approximately 1.5 m/s. At first glance this result looks quite demanding, but as mentioned earlier - the force is quadratic function of velocity. The analysis shows that system will be able to meet the resolution requirements of 0.5 m/s at wind speed of approximately 3 m/s; and 0.1 m/s at 7 m/s. For the maximum wind speed of 75 m/s will be needed 2030 LSB, which is within the capabilities of the current system. The achieved measurement resolution at this point will be approximately 0.02 m/s. Figure 4 shows the family of diagrams of ADC response per wind velocity for the set of load cells with different sensitivity.

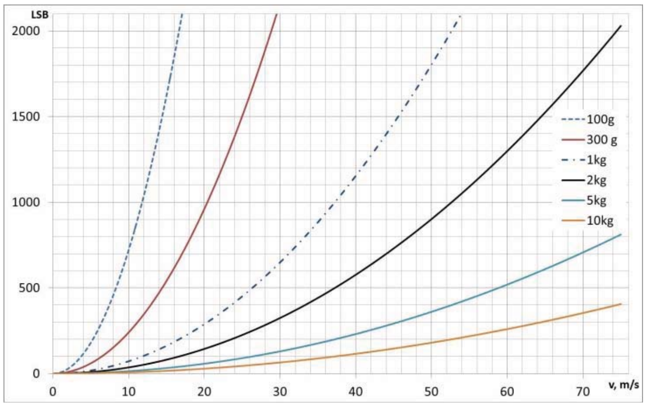

Figure 4 – System Response Characteristics

As the analysis shows, using 300-g load cell would achieve the reference measurement requirements at the bottom level of the scale, but the maximum will be limited to approximately 29 m/s. This presumes usage of a model with two pairs of load cells. In this case the length of the covering coat should increase to approximately double size, which will double also the applied wind force. Figure 5 shows the change in the characteristics for the same set of load cells, but with twice longer covering coat tube.

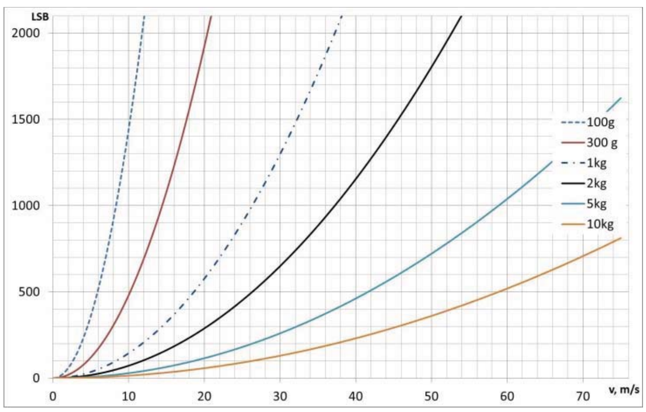

Figure 5 – System Characteristics – Long Coat Model

For this model, combination of 1-kg and 5-kg load cells would meet the reference requirements for the entire range. One item that should be studied for this case is the mechanical strength of the model.

Alternatively, the requirements for the entire range could be achieved with usage of programmable gain amplifier. Figure 6 shows a family of characteristics for 1-kg load cell with different gain.

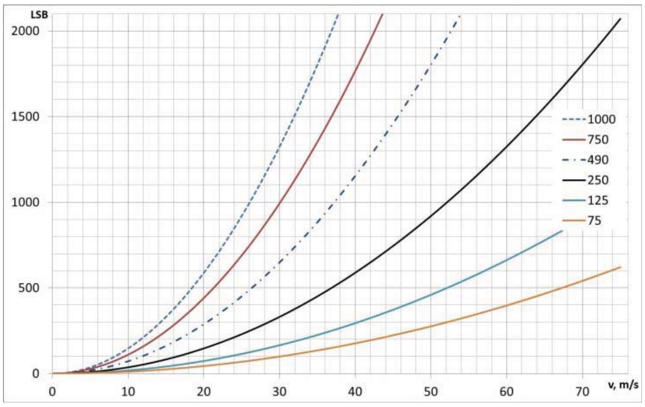

Figure 6 – 1-kg Load cell characteristics – gain model

In the current model 1-kg load cell could meet the requirements for the entire range by changing the amplifier's gain between 1000 and 250. Same result is achieved with 2-kg load cell and amplification between 2000 and 500. This provides additional options for the mechanical strength of the model, but may require precautions for signal to noise ratio.

IV. AIR DENSITY VARIATIONS

As stated above, air density is a parameter that varies with changes in temperature, pressure, and humidity. To evaluate the need of inclusion of humidity effect in air density calculation, a deviation profile of air density over temperature is prepared for 5 cases of relative humidity. Profile is based on equation (5) and shown on figure 7.

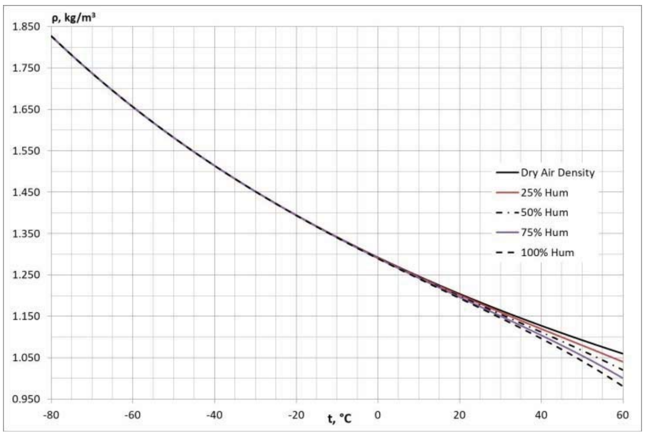

Figure 7 – Air density vs. temperature

As the results show, air density is practically affected by humidity for temperatures above 0 °C (-0.23%) and at 60 °C can reach a maximum of -7.46%. At first it may seems strange that the humid air density is actually lower than dry air, but this effect is normal due to lower molar mass of water vapor (18 g/mol) compared with dry air (28 g/mol).

Air density is sensitive to temperature – approximately 1% increase per every 3 °C of temperature drop. So an approximate drag force variation of ±25% should be expected.

Estimated pressure sensitivity is also strong, as shown on figure 8.

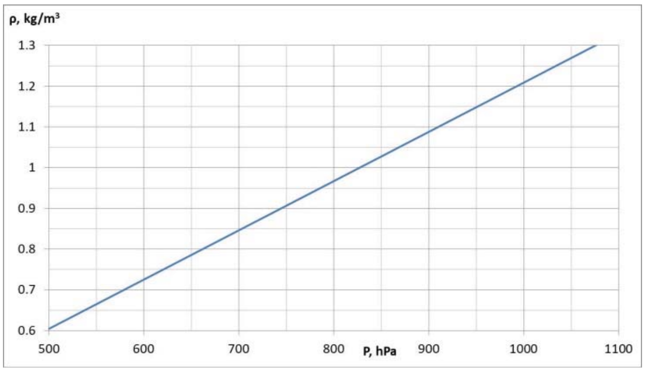

Figure 8 – Air density vs. pressure

Dependency is nearly 1% increase of air density per every 10 hPa increase of pressure. The expected effect over the drag force for the full measurement scale is almost ±30%.

V. CONCLUSION

Analysis of the initial prototype model shows that it is well determined and functional, but not able to meet the reference requirements. There are two options for improving the model that are currently under development – usage of two pairs of load cells in a common covering coat, and usage of a programmable gain amplifier. Each of them requires additional study.

Air density variations may have a significant effect over measured drag force, therefore should be taken into account during sensor selections and mechanical strength calculations.

ACKNOWLEDGEMENT

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