Vibrating-Wire, Supercooled Liquid Water Content Sensor Calibration and Characterization Progress

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Background

• Inflight icing of aircraft remains a hazard to the aviation community.

• Providing operators with real-time information of atmospheric icing conditions is a means to reduce hazard by operationally minimizing exposure.

• NASA has been developing icing remote sensing technology to provide the necessary information, but the technology requires validation through in-situ measurements.

• NASA funded Anasphere, Inc., through the SBIR program, to develop and calibrate weather balloon-borne, supercooled liquid water content (SLWC) sensors.

• NASA conducted a field campaign at the NASA Glenn Research Center (GRC) in Cleveland, OH during winter 2015 to develop a validation database using the Anasphere SLWC sensors.

• Significant effort has been made to calibrate and characterize these sensors including facility development and experimental testing.

• Progress has also been made to understand an unexpected behavior observed in the SLWC sensor data from the winter 2015 campaign.
SLWC Sensor Description

• The weather balloon instrument package used during the field campaign included the iMet-1-RSBN Radiosonde and the vibrating-wire, SLWC Sensor.

• The measurement principle behind the SLWC sensor is that ice accretion along the wire leads to a decrease in the natural frequency of the wire.

• Vertical profiles of SLWC can be derived from the time history of the measured wire vibration frequency and the ascent speed.

• The 0.6 mm steel wire is periodically “plucked” using a servomotor with a magnet attached to a short support.

• A thin film piezoelectric sensor, sandwiched between a silicon rubber structure, measures the wire vibration frequency.

• An Anasphere, Inc. proprietary signal processing method is used to determine the natural frequency every 3 seconds.
Anasphere, Inc. developed a low speed icing tunnel for calibration testing of the SLWC sensors.

The facility is a closed circuit, fan driven, icing tunnel with a 30 cm by 30 cm test section.

Steady airspeeds around 5 m/s are achieved in the test section
- The nominal ascent rate of the winter 2015 weather balloons is 5 m/s.

The tunnel is insulated and the heat exchanger is capable of cooling to subfreezing temperatures between -15 °C and -10 °C.

A single Spraying Systems Co. 1/4J-SS air-atomizing nozzle is used to create the supercooled cloud.
- Air and water pressure are controlled independently.
- Water supply is chilled to ensure supercooling.
Calibration: 
Tunnel Testing

- Testing was carried out in two separate phases
  - 1st Phase: SLWC Sensor and PDI
  - 2nd Phase: Icing Blade

- The SLWC Sensor frequency data and drop size and speed distributions were acquired during the 1st Phase.
  - Vibration plane of SLWC Sensor was orthogonal to the flow direction
  - PDI was non-intrusive and situated upstream of the SLWC Sensor housing

- Independent measurements of SLWC were acquired using an icing blade during the 2nd Phase.
  - Blade used due to concerns about hotwire instrument operability, data fidelity and heat load on the facility
  - 0.64 mm thick blade
  - Spray times were varied to obtain approximately 0.6 mm thick ice accretion
Calibration:
Data Reduction – SLWC Sensor

• **SLWC** is calculated using the frequency profile
  - The time derivative of the frequency, \( df/dt \), is the driving term
  - The terms \( f, f_0, \varepsilon, D \) and \( u \) are the frequency, clean-wire natural frequency, collection efficiency, wire diameter and ascent speed, respectively
  - The term \( b \) is a coefficient related to the physical characteristics of the wire

\[
SLWC = \frac{2b f_0^2}{\varepsilon D f^3} \frac{df}{dt}
\]

• The trends for all case are linear and all have \( R^2 \) values greater than 0.996.
  - Trends were used instead of typical generalized central differencing method that have been used for atmospheric soundings.

• **SLWC** is calculated using the blade equation (Ref. 2)

\[ SLWC = \frac{\rho S}{\varepsilon ut} \]

- The terms \( \rho \), \( S \), \( \varepsilon \), \( u \) and \( t \) are the ice density, the ice accretion thickness, collection efficiency, flow speed and time, respectively.

• \( \rho \) is calculated using the Macklin empirical equation (Ref. 3)

\[ \rho = 110\left(-5 \times 10^5 \frac{d_{v0.5}u}{T_s}\right)^{0.76} \]

- The terms \( d_{v0.5} \) and \( T_s \) are the MVD and surface temperature, respectively.
- Soft rime was observed during testing.
- Soft rime ice densities range from 200 to 600 kg/m³.

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• The calculated SLWC profiles rise to varying degrees, between 3% and 17%.

• This effect may be due to general form of the SLWC equation.
  - $f^3$ in the denominator, where $f$ is a decreasing term with increasing ice accretion.

• Other effects such as cloud recirculation may also be contributing factors, but were not investigated in this work.

• The linearity of the frequency profiles suggest test section SLWC remained constant.
The correlation between the two measurements is promising, agreeing to well within ±25% in several cases.
Ice Accretion Analysis:

- Images of the ice accretion on the SLWC Sensor were taken during testing.
- A ‘shadow zone’ exists which has not be previously documented.
- The length of the wire with no ice accretion, $L_1$, increased by approximately 11%.
- Effect on the calculated SLWC was found to be negligible.
  - Increased SLWC in all cases by 0.75%
  - Parametrically, SLWC increases less than a few percent for $L_1$ values approaching 50% of $L_0$
• The gradual increase, or drift, in the frequency profiles is observable.

• The drift is linear when plotted on a logarithmic pressure scale, and does not appear to be affected by the presence of icing conditions.
Sensor Data Drift:
Data Analysis (2 of 2)

- The primary suspect sources include:
  - Increased modulus of elasticity of the silicone rubber clamping structure, reducing the effective length of the wire by decreasing the clamp’s structural pliability.
  - Increasing modulus of elasticity of the steel wire, thus stiffening the wire.

Relative Comparison of Thermal Effects
A SLWC sensor was tested in a controlled laboratory environment to better understand this behavior.
- A thin thermocouple used to measure the temperature of the silicone rubber square.
- The sensor was placed in a freezer with a controllable temperature, and the thermocouple temperature and vibration frequency were recorded over a period of 30 minutes.

The data clustering near -60 °C for some cases is due to the weather balloons reaching the isothermal layer near the tropopause.

The trends for the balloon soundings and the laboratory test are similar indicating the effect is thermal.
The data was corrected by fitting a trend and removing the difference between the trend and clean wire natural frequency.

The maximum SLWC only increases marginally, approximately 3%, but the integrated liquid water, ILW, increases by 20% for this case.
Summary and Conclusions

• Significant progress has been made calibrating and characterizing vibrating-wire sensors—the goal of this work.

• Preliminary results are promising, based on the agreement between the sensor and blade.

• An expanded calibration database is needed.

• The gradual increase in SLWC without corresponding decrease in frequency suggests that the equations may need to be modified to handle larger mass formations.

• The extent of ‘shadow zone’ was identified and shown to have negligible effect on results.

• Possible causes for the frequency drift in the winter 2015 campaign data were investigated.

• A method to correct winter 2015 campaign data was developed and presented.
Questions?