Flywheel Calibration of Coherent Doppler Wind Lidar

Pedersen, Anders Tegtmeier; Courtney, Michael

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**Motivation**

“Lidars are absolute instruments” is a sentence often heard, and by that is meant, that given the laser wavelength and the sampling frequency, we are able to calculate the measured radial speed through the well-known equation: \( v_r = \frac{\lambda}{2L} \cdot \Delta f \). There are no empirical constants that have to be found through a calibration as is the case for e.g. cups or even LDAs. Why then do we claim that lidar calibration is necessary anyhow? Probably the most direct answer is that without a calibration we cannot know that the lidar is getting it right. There could be wrong constants or some subtle errors in the algorithm. Only by comparing to a known ‘truth’ can we be completely sure that the lidar gives the correct speed.

**Main uncertainty components**

- Wheel diameter: 0.1 mm
- Relative uncertainty \( u_l = \frac{0.5}{10} \cdot 10^{-4} \)
- Frequency from tachometer to speed conversion: 10 ppm
- Relative uncertainty \( u_{\Delta f} = 1 \cdot 10^{-4} \)
- Tilt angle resolution: 0.01
- Relative uncertainty \( u_{\Delta \theta} = \frac{0.01}{\text{rad}} \cdot \frac{1}{2} = 2 \cdot 10^{-4} \)
- Combined relative uncertainty \( u_{\text{combined}} = \sqrt{u_l^2 + u_{\Delta f}^2 + u_{\Delta \theta}^2} = 4.5 \cdot 10^{-4} \)

**Calibration rig**

A simple model relating the error in measured speed due to non-tangential skimming angle, \( \psi_s \), to the inclination angle, \( \theta \), has been developed.

**Function of speed**

**Function of focus distance**

**Model**

A simple model relating the error in measured speed due to non-tangential skimming angle, \( \psi_s \), to the inclination angle, \( \theta \), has been developed.

By assuming the laser beam is infinitely narrow and that \( \theta \) and \( \psi_s \) are both small, the relation between \( \theta \) and \( \psi_s \) can be found from simple geometrical considerations:

The tringle formed by the vertical radius, the length \( d \), and back to centre is Pythagorean:

\[
R^2 = R^2 + d^2 = (R + b)^2 = (R + b)^2.
\]

Using that \( Rb \ll 2R \):

\[
R^2 = 2RLb + L^2b^2 = 2RLb,
\]

the skimming angle is found as:

\[
\psi_s = \sin \psi_s = \frac{d}{R} = \frac{2Lb}{R}.
\]

Now, the lidar only measures the speed component along the line-of-sight, thus \( \frac{v_{\text{lidar}}}{\sin \psi_s} = \frac{v_{\text{radial}}}{\sin (\psi_s + \theta)} = \frac{v_{\text{radial}}}{\sin (\psi_s + \theta)} \)

and by Taylor expansion of the cosine term a simple expression for the speed ratio error is reached:

\[
\frac{v_{\text{lidar}}}{\sin \psi_s} = 1 + \frac{v_{\text{radial}}}{\sin (\psi_s + \theta)} = \frac{1}{1} - \frac{Lb}{R}.
\]

Finally, the speed ratio error sensitivity is given as

\[
\frac{\partial v_{\text{lidar}}}{\partial \psi_s} = \frac{L}{R}.
\]

which for the actual calibration rig becomes

\[
\frac{\partial v_{\text{lidar}}}{\partial \psi_s} = \frac{1.58 \text{ m}}{2.87 \text{ m}} = 0.56 \text{ s/m}.
\]

**Results**

**Conclusion**

- Calibration rig built and running
- Model for measurement error as function of inclination angle made
- Measurements agree well with model
- Method stable over wide range of speeds
- The main uncertainties have been identified
- The line-of-sight speed can be calibrated to an uncertainty of approximately 0.5%