Studies on acoustic method for determination of the refractive index of air

MIKES

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Introduction

The accuracy requirements of position measurements are increasing in both laboratory and production applications. In laser interferometric position measurements the environmental conditions affect the results due to they effect on refractive index of air. For that reason, air pressure, temperature and humidity has to be measured accurately. Especially near or inside production equipment temporal and spatial temperature variations may be large and fast, which make measurement of actual temperature difficult with traditional methods. For example, with temperature sensors one can measure temperature only at single points near the actual beam path. The response time of the thermometers are also rather long, from several seconds to a few minutes, i.e. fast temperature changes cannot be measured either.

Speed of sound is about two thousand times more sensitive to temperature variations than refractive index of air, a fact which can be used for accurate determination of the refractive index of air. The speed of sound can be measured simultaneously with the laser interferometric measurement and over the same path utilising ultrasonic piezo transducers fixed to the optical components of the interferometer. The real-time and real-place refractive index can be determined by using equations for the effective air temperature and refractive index or air as a function of speed of sound (f = 50 kHz), pressure, humidity and CO_2 concentration. [1, 2]

Equations

$$f(c,p,x_w,x_c) = b_0 + b_1 c + b_2 c^2 + b_3 x_w + b_4 x_w^2 + b_5 x_w^3$$
$$+ b_6 p + b_7 p^2 + b_8 x_c + b_9 x_w c + b_{10} pc + b_{11} x_w p$$

- Developed and validated by MIKES [1, 2]
- Equations are based on our experimental results for speed of sound and partly derived from Cramer equation for speed of sound [3] and Edlén equations for refractive index of air [4].

- Temperature range 19…22°C
- Humidity range 16…51%RH
- Pressure range 1000…1040 hPa
- CO_2 concentration range 350…450 ppm
- Valid for group velocity of ultrasound f = 50 kHz

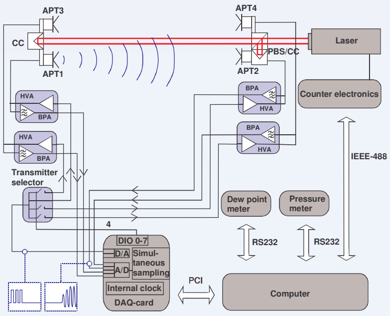
	Refractive index n_{eff}		**Temperature** t_{eff}
b_0	1.000682285172		-540.0160
b_1	-3.96955965	$\times 10^{-06}$	1.630328
b_2	5.7733599	$\times 10^{-09}$	0
b_3	1.364841	$\times 10^{-04}$	86.74
b_4	-8.8637	$\times 10^{-04}$	972
b_5	2.5538	$\times 10^{-02}$	-27400
b_6	7.79906651	$\times 10^{-09}$	-0.000000111
b_7	1.40365	$\times 10^{-17}$	0
b_8	9.92	$\times 10^{-06}$	145
b_9	-3.58288	$\times 10^{-07}$	-0.5150
b_{10}	-1.49002013	$\times 10^{-11}$	0
b_{11}	3.26201	$\times 10^{-10}$	0

Setup

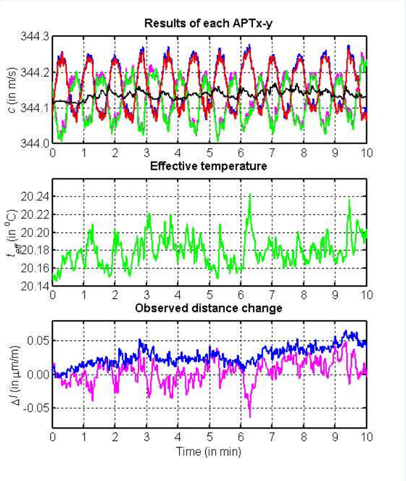
- Distance measurement (l)
  - heterodyne laser interferometer
- Time of flight of ultrasound (tof) measurement
  - two pairs of piezo transducers (APT1-2, APT3-4)
  - short ultrasound burst of 50 kHz is transmitted and received in turn
  - cross correlation algorithm

➔ $c = l/tof$

- t_{eff} and n_{eff} can be calculated as a function of speed of sound (c), pressure (p), mole fraction of water (x_w) and CO_2 concentration (x_c)
  - ➔ $t_{eff} = f(c, p, x_w, x_c)$
  - ➔ $n_{eff} = f(c, p, x_w, x_c)$
- Acoustic and interferometric measurements are done
  - symmetrically ➔ eliminates Abbé error
  - simultaneously ➔ compensate also fast changes
  - over the same distance
  - ➔ t_{eff} and n_{eff} along the beam path
- Software and hardware is updated for faster measurements (~1/s)



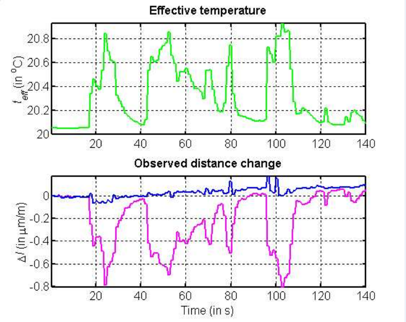
Operation under simulated demanding industrial conditions



Airflow

- Airflow affects the speed of sound.
  - ➔ Errors in c
- Airflow in both directions in turn by two fans
  - Max ~0.2 m/s
  - Average ~0.1 m/s
- The effect of airflow and the compensation is shown in figure adjacent
  - Speed of sound measured with
    - APT1 → 2 (——)
    - APT2 → 1 (——)
    - APT3 → 4 (——)
    - APT4 → 3 (——)
  - Average of the acoustic measurements (——)
  - Most of the variations in average speed of sound are caused by temperature variations (~50 mK, ——)
  - variations in acoustically compensated (——) distance are significantly smaller than in uncompensated (——)

➔ Effect of air flow can be well eliminated by bi-directional acoustic measurement



Warm turbulent air

- Causes fast and local temperature variations
  - ➔ very difficult to compensate with traditional methods
- Warm (max temperature ~23…25°C) air were blown across to the measurement path.
- A fixed distance (2.9 m) was measured with laser interferometer.
  - Maximum changes in t_{eff} ~0.8°C (——)
  - Changes in uncorrected l ~0.8 µm/m (——)
  - Changes in acoustically corrected l ~0.05 µm/m (——)

➔ Excellent compensation

Conclusions

- Acoustic method gives effective t and n for interferometer; time and place are equivalent to interferometric measurement
- Faster operation of the test set-up allows better online correction of interferometric distance measurement
- Effect of airflow on speed of sound measurement is well compensated by bi-directional measurement
- Large temperature gradients and fast temperature changes can be compensated
  - e.g. effect of turbulent warm air can be reduced from 0.8 µm/m to 0.05 µm/m
- Accuracy of interferometric length measurements can be increased by acoustic method
  - ➔ high accuracy length measurements in laboratory conditions
  - ➔ industrial applications under workshop conditions
- Uncertainty of the setup: 25 mK, 2.6×10^{-8} and ~0.03 µm/m for t_{eff}, n_{eff} and l, under laboratory conditions

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