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Low Cost Hot-element Anemometry Verses the TFI Cobra

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Abstract

A group of low-cost hot-element anemometers were evaluated for their ability to measure wind speeds in smooth and turbulent flow for the purpose of measuring replicated atmospheric boundary layer conditions in wind tunnels. The sensors' directional dependency was investigated and found to be predictable though non-linear; therefore the sensors are useful when the direction of the wind flow is reasonably well known. However, highly turbulent flows where large angle fluctuations are present, dependency on direction will be problematic. The frequency response of the sensor drops off at above 10Hz. All measurements were referenced against a Turbulent Flow Instrumentation (TFI) Cobra probe.

Introduction and Objectives

Multi-point simultaneous measurement of fluid flow is usually expensive due to either the cost of multiple sensors (e.g. hot-wire or hot-film anemometers) or optical methods interrogating across a plane in the flow (e.g. Particle image velocimetry (PIV)).

In unsteady flows, such as model-scale replication of the atmospheric boundary layer and the velocity fields around buildings, it is often desirable to have multiple sensors being deployed where directional, temporal and thermal characteristics of the sensors need to be known. In particular when attempting to generate a variety of scale atmospheric boundary layer profiles it is usual practice to employ a range of upstream grids and fences. The different profiles generated need to be evaluated rapidly and then refined experimentally to ensure reasonable matching to chosen atmospheric boundary layer profiles. Currently this is usually performed via a single traversed sensor or a few relatively high-cost sensors placed strategically through the profile.

The objective of the work documented in this paper is to evaluate the key response parameters of a set of low cost hot-element anemometers. The sensors were exposed to smooth wind flow within the aerospace wind tunnel (AWT) located at the RMIT Bundoora East campus and in turbulent flow in the industrial wind tunnel (IWT) – also at RMIT.

The key response criteria tested were directional dependency and average velocities in smooth flow and frequency response in turbulent flow. Details of calibration and integration into a system that can provide rapid feedback at multiple points in the field are also covered.

Sensing and Display System

Sensors

Recently advances in hardware, particularly micro-electromechanical systems (MEMS) technology, have enabled relatively cost effective thermally based sensors to be mass-produced. One such sensor is the revision P wind sensor from Modern Device (1000th the cost of the TFI Cobra probe) (figure 1) which emerged from earlier revisions which were used as human breath sensors.

The hot-element anemometers (rev-P wind sensors) were compared with a high precision multi-hole Cobra probe. On close inspection the heated element on the hot-element anemometer is rectangular in section (surface mount device (SMD) thermistor) suspended within a gap in the printed circuit board (PCB).

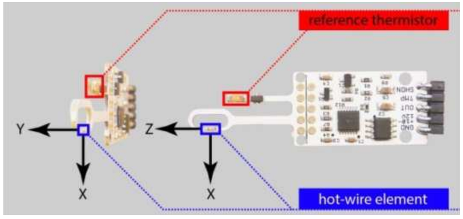

Figure 1. Rev-P hot-element anemometer from Modern Device.

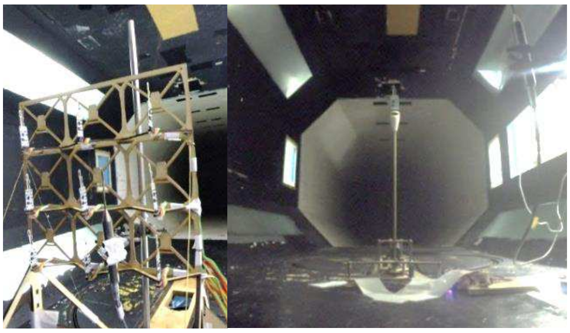

Figure 2. A 3 by 3 matrix of hot-element anemometers for speed calibration (left) and single hot-element anemometer mounted on the directional dependency rotational rig (right) - both in smooth flow within the AWT.

The multi-hole Cobra probe used as reference has been heavily studied in various turbulent flow conditions with high precision measurements [1,2,3,7,10].

Software developments have allowed for rapid calibration of multiple instruments and the use of multiple anemometers used within the flow field. This leads to the desired end-use of the anemometers – a rapid feed-back system capable of efficient calibration and evaluation of relatively low turbulence intensity and wind velocity profiles and fluid systems where the direction of fluid flow is reasonably well known.

Data Acquisition System

The Cobra probe and hot-element anemometer were sampled at 1250 Hz and 300 Hz, respectively, in smooth flow conditions for speed calibration.

The Cobra probe and hot-element anemometer were sampled at 1250 Hz and 100 Hz, respectively, in smooth flow conditions for directional dependency evaluation.

Both instruments were sampled at 5000Hz within turbulent flow to cover the broadest applicable frequency spectrum.

There were multiple data acquisition units used including an Arduino Uno (10 bit resolution), Teensy 3.1 (13 bit resolution) and a PCI-6034E DAQ (16 bit resolution) to cater for high frequency data acquisition, number of inputs or/and ease of control of the rotational rig.

Display Software (or System)

Two outputs from the hot-element anemometer were recorded: the ambient air temperature from the reference thermistor and the output voltage from the hot-element element (see figure 1). These two values were correlated with the wind speed measured by a reference Cobra probe to create a 3D function. The reference thermistor data was used where possible; otherwise the ambient air temperature was used (measured with a high precision temperature probe (±0.1ºC)).

Wind Tunnels and Calibration System

RMIT Aerospace and Industrial Tunnels

The anemometers were calibrated within smooth flow in the AWT. Measurements within this tunnel were referenced against a TFI Cobra probe. Smooth, almost homogeneous flow through its cross section was observed. Smooth flow in both tunnels was also measured with a NPL-modified head pitot-static probe connected to Baratron reference pressure transducer. The test section is a $1.1 \times 1.3m$ chamfered section (octagonal section) with a section length of $2.1m$.

The hot-element anemometers were placed in a 3 by 3 grid at 100mm centres. The two outputs from each sensor were recorded with 18 analogue input pins on a Teensy 3.1 processor. A reference voltage of 3.33 V was used. A sample size of 45 sensors was used to evaluate the variation in the sensors ability to measure wind speeds accurately. Variation of wind speed across the face of the apparatus was <0.2m/s and corrections were made to insure wind speeds (as measured by the cobra probe) were reliable to within 0.1m/s.

Initially a quick method of calibration was used with Rhino3d and Grasshopper3d/Firefly to rapidly gain an understanding of the curvature of the calibration surface and to quickly apply this surface to get real-time feedback during the directional dependency experiments.

However, the calibration procedure required within grasshopper3d is very computationally heavy and can take a matter of minutes when attempting to post process thousands of values using an object oriented intersecting process. So, the calibration process was migrated to Matlab for en mass calibration (figure 3).

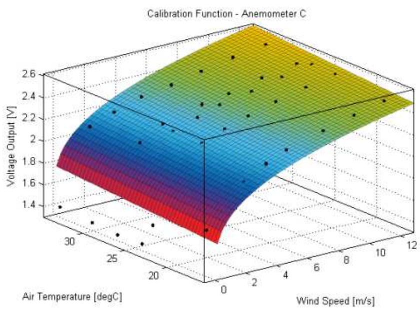

Figure 3. Sample calibration function (anemometer C).

The best fit resultant function was a parametric function with a linear and power curve component for the temperature verses Voltage output and wind speed verses voltage output, respectively.

$$V_{out} = a + bT + cv^{d} \tag{1}$$

Where:

$V_{out} = voltage\ from\ anemometer\ [V]$

$T = ambient\ temperature\ [°C]$

$v = wind\ speed\ [ms^{-1}]$

$a, b, c, d = constants$

Transposing to make wind speed the subject the expression becomes:

$$v = \left\{\frac{(V_{out} - a - bT)}{c}\right\}^{1/d} \tag{2}$$

The robust least absolute residuals (LAR) surface fitting method was chosen to remove the clear outliers from the function derivation. The resulting R-square value was increased by ~0.08 when compared to non-robust methods. The resulting surface for each sensor had an R-square of ~0.96. The Trust-Region fitting algorithm was used in this instance.

Method and Results

Angle Response in Smooth Flow

The rotational rig was centrally positioned in the AWT within smooth flow and rotated at 10º increments from -180º to +180º about both axes. 512 values at 100 Hz were averaged at each increment to give the following polar graphs (figure 4) where the response of three typical anemometers can be seen.

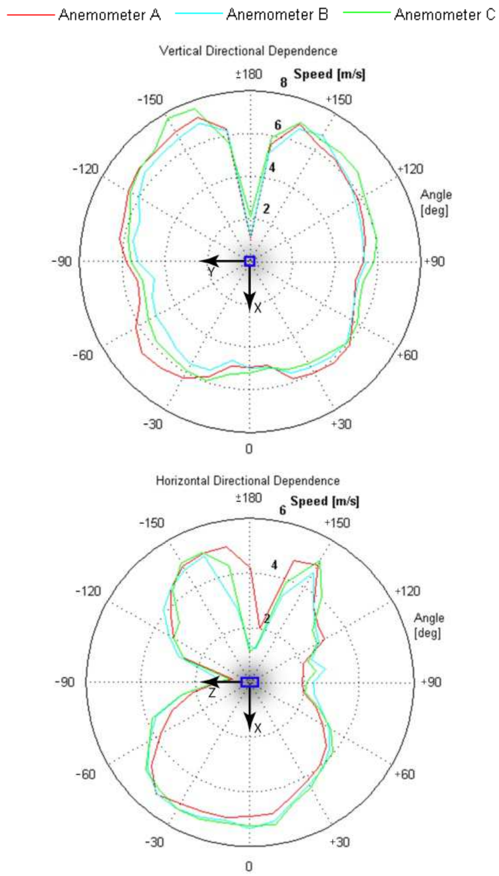

Figure 4. Directional dependency of average speeds about the X-Y plane (top) and the X-Z plane (bottom).

It is apparent that there are considerable asymmetrical variations in wind speed about both axes, though more prevalent in the X-Z plane, deviations of ±0.6 ms^{-1} through a 45º cone about the X-axis. The asymmetry through ±45º about the X-axis is assumed to be caused by the effects of the wake region created by the sensor PCB and quiet possibly the effect of the rotational rig. It seems probable that the circular section of the rotational rig's sensor mounting head in this plane seems to significantly affect the flow through +10º to +60º about the Y-axes. Though, based on the data obtained, it is recommended to slightly tilt the sensor -15º about the Y-axis with respect to the predominant wind direction. Furthermore, both sensor B and sensor C are extremely similar in this region and upon further inspection of Sensor A, it is apparent that its heated element is slightly disoriented (tolerance issue in the manufacturing process).

A potential improvement may be made by orienting the heated element (SMD thermistor) -90º about the Z-axis. This would solve the dip in speed through the ±15º region about the X-Y plane. The result may flatten the speed variation considerably since the variation in speed about the +20º to +160º will only be due to the PCB form factor.

Frequency Response in Turbulent Flow

Turbulent flow in the IWT is limited to nominally zero pitch and yaw with no grid with ~1.7% TI [8]. The wind flow was augmented with the grid shown in figure 5. Turbulence levels and spectral data were obtained from the hot-element anemometer and reference Cobra probe (see Table 1).

Turbulent flow measured with Turbulent Flow Instrumentation (TFI) Cobra probe is well documented [1,2,3,7] and more information can be found about the Cobra probe from the TFI website [10].

Figure 5. The hot-element anemometer (left) and multi-hole Cobra probe (right) in turbulent flow in the IWT (6m downstream from grid).

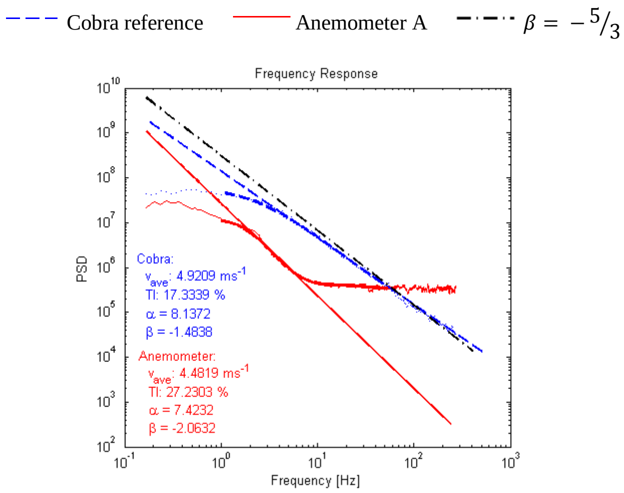

Figure 6. Example Power Spectral Density (PSD) verses Frequency plot showing smoothed values, polynomial log fits and linear power best fit functions on most significant regions – the -5/3 Kolmogorov slope is displayed as reference.

Linear power functions follow the rule:

$$y = 10^{\alpha} x^{\beta} \tag{3}$$

Where:

$y = power\ spectral\ density$

$x = frequency\ [Hz]$

$\alpha = log_{10}(y) when\ \beta\ is\ equal\ to\ 0\ (y - translation)$

$\beta = slope\ of\ the\ PSD\ distribution$

Multi-hole Cobra probe reference		Hot-element anemometer Sensor A	Hot-element anemometer Sensor B	Hot-element anemometer Sensor C
	v_{ave} [ms^{-1}]	3.50 / 3.43	3.52 / 3.77	3.52 / 3.45
		4.92 / 4.49	5.00 / 5.17	4.92 / 5.29
		6.04 / 6.13	6.00 / 6.33	6.00 / 5.81
	TI [%]	17.5 / 29.0	17.2 / 23.2	17.5 / 25.5
		17.3 / 27.4	16.6 / 20.2	17.0 / 23.8
		17.3 / 25.8	17.1 / 18.4	17.5 / 22.0
	β	-1.48 / -2.77	-1.47 / -2.77	-1.49 / -2.69
		-1.37 / -2.23	-1.38 / -2.74	-1.37 / -2.15
		-1.32 / -2.33	-1.30 / -2.59	-1.30 / -2.23

Table 1. Averages of average speed (v_{ave}), turbulence intensity (TI) and slope of the PSD distribution (β) over 10 samples taken in turbulent flow.

	Hot-element anemometer		
	Sensor A	Sensor B	Sensor C
v_{ave} Δ_{max}	-0.10	0.29	-0.15
	-0.49	0.21	0.44
	0.18	0.39	-0.43

Table 2. Maximum deviations (Δ_{max}) in average wind velocity (v_{ave}) across 10 samples taken in turbulent flow.

It should be noted that the hot-element anemometer seems to be capable of measuring wind speeds to within ±0.5ms^{-1} in comparison with the Cobra probe within the turbulent flow generated in the IWT (see table 2). Since the angle of wind flow did not exceed the ±45º cone of acceptance of the Cobra probe (100% of data fell on the Cobra probe calibration zone) [1,2,3,7,10].

The errors in TI measurements recorded by the hot-element anemometers are very significant (see table 1). However, sensor B seems to be performing considerably better – further experiments are required to deduce the cause.

Display Software (or System)

The output of the rev-P sensors can be easily managed by a standard Arduino board. And when coupled with software capable of serial COM port communication, near real-time feedback from the wind sensor can be observed (see figure 7). The anemometers are solid state and require minimal setup requirements after calibration. See more information about using the previous generation rev-C sensors and near real-time feedback in conference papers [5,6].

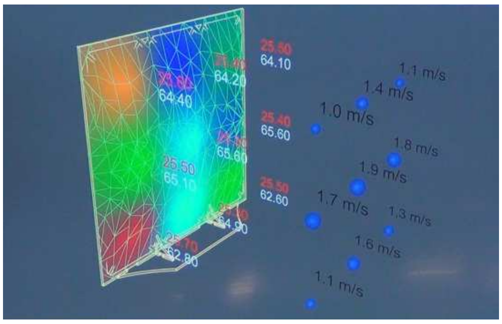

Figure 7. Example real-time visualisation of the 3x3 wind sensor, temperature and relative humidity matrix used in the SmartGeometry 2014 workshop in Hong Kong [11].

Discussion

The ability of the rev-P sensors to measure average wind velocities is, as expected, dependent on temperature fluctuation of the ambient air. However, either the reference thermistor or a reliable ambient air temperature measurement is reliable (in a reasonably homogeneous thermal system). Though, each sensor would require some degree of calibration. Further analysis is needed to confirm, but from a qualitative estimate the sensors would require, at absolute least, a measurement of a voltage to be added to the constant 'a' in equation (2) [9].

Turbulence intensities measured by the hot-element anemometers were generally considerably higher than the cobra probe reference. The cobra probe is an excellent reference within highly turbulent flows [1,2,3,7,10]. The increase in turbulence intensity (TI) is most probably caused by the directional dependency of the hot-element anemometer. The cone of acceptance of the Cobra probe covers ±45º in both orthogonal directions with 100% of data that fell on the calibration zone during experimentation in turbulent flow [1,2,3,7,10]. Whereas, the hot-element anemometer is only reliable from +45º to -10º about the Y-axis and does not reliably cover this angular range about the Z-axis.

The response of the anemometer appears to reduce considerably over frequencies of about 10 Hz – and therefore the TI will be affected to some degree – depending on how much noise there was in the system during measurement. Accumulated affects from electrical inductance, temperature dependent responses and directionally dependent variations will contribute to the noise – which is an almost chaotic interrelationship – so it is difficult to diagnose the specific cause from the data set presented.

Concluding Remarks

Unfortunately, the rev-P sensor, as it stands, cannot be reliably used in turbulent flow for frequency measurements or excessively directionally variable flows. However, there is reason to suggest the sensors are capable of measuring average wind velocities where the direction of wind flow is reasonably well known (to within $\pm 0.5 ms^{-1}$ accuracy). The angular response could be improved using a cylindrical hot-wire element with the circular section oriented through the X-Y plane or possibly rotating the heated element -90º about the Z-axis.

The hot-element anemometers will be useful for wind tunnel velocity profile measurement since the flow direction well downstream from grids is reasonably known and software outputs velocity measurements in close to real time. However, TI measurements are not possible at this stage. Though, applying a low-pass filter to the frequencies below 10Hz may improve the TI results.

They may also be used in wind engineering for documentation of ground level winds in a similar manner to Irwin probe (anemometer probe used en mass) [4].

Acknowledgments

This research is part of a larger ARC discovery project: 'Integrating architectural and mathematical knowledge to capture the dynamics of air in design'. The apparatus shown in figure 2 (left) was chosen to replicate the system to be used in further experiments with the hot-element anemometers in a mini wind tunnel in the Smart Geometry 2014 workshop in Hong Kong [11] (more information can be provided through email). Raphael Moya Castro for his enthusiasm and collaboration in previous experiments with the rev-C hot-element anemometer [5,6]. Paul Badger for the supply and manufacture of the rev-P sensors from Modern Device [9].

References

[1] Chen, J., Fletcher, D.F., Haynes, B.S. and Hooper, J.D. *Validation of the cobra probe using turbulence measurements in fully developed pipe flow*. Proc. 13th Australasian Fluid Mech. Conf., Melbourne, 1998.

[2] Chen J., Haynes B.S., and Fletcher D.F., *Cobra Probe Measurements of Mean Velocities, Reynolds Stresses and Higher-Order Velocity Correlations in Pipe Flow*, *Experimental Thermal and Fluid Science*, Vol. 21, 2000, pp.206-217.

[3] Hooper, J.D., and Musgrove, A.R., *Reynolds Stress, Mean Velocity, and Dynamic Static Pressure Measurement by a Four-Hole Pressure Probe*, e*xperimental Thermal and Fluid Science*, Vol. 15, No. 4, 1997, pp.375-383.

[4] Jirsák, M., Zacho, D., Michálek, P., Jandová, K., *Irwin Probe Callibration and its Use at Investigation of Pedestrian Wind Conditions in Vicinity of High Buildings*, Institute of Thermomechanics AS CR, v.v.i., Prague, 2008.

[5] Moya, R., Prohasky, D., Watkins, S., Ding, Y., Burry, J., Burry, M. *Aerodynamic strategy applied in an urban shelter design, Simulation and analysis of aerodynamic phenomena in an urban context*, eCAADe. Conf., Northumbria University, Newcastle, 2014.

[6] Prohasky, D., Moya, R, Watkins, S., Burry, J., Burry, M. *Wind sensing with real-time visualisations for Designers, An approach to understanding wind phenomena for pedestrian comfort using low cost wind sensors*, eCAADe. Conf., Northumbria University, Newcastle, 2014.

[7] Watkins, S., Mousley, P., and Hooper, J., *Measurement of Fluctuating Flows Using Multi-Hole Probes*, Proceedings of the Ninth International Congress on Sound and Vibration, 8-11 July, Orlando, Florida, International Institute of Acoustics and Vibration, Alabama, USA, 2002.

[8] Watkins, S., *Wind Tunnel Modelling of Vehicle Aerodynamics: With Emphasis on Turbulent Wind Effects on Commercial Vehicle Drag*, PhD Thesis, Department of Manufacturing and Process Engineering, RMIT University, 1990.

[9] ModernDevice, (2014). *Rev P Wind Sensor Data*, http://moderndevice.com/uncategorized/rev-p-wind-sensor-data/

[10] Turbulent Flow Instrumentation (2014). *Cobra Probes in Use*, http://www.turbulentflow.com.au/Products/CobraProbe/CobraProjects.php

[11] Smart Geometry 2014 Urban Compaction Workshop, (2014). *Private Microclimates*, http://smartgeometry.org/index.php?option=com_content&view=article&id=249&Itemid=201