Practical issues for pedestrian wind comfort prediction: surface-level wind speed sensors

D. Banks*, K. Haas, Y. Fewless, J. A. Peterka, R. O. Denoon

CPP Wind Engineering and Air Quality Consultants, 1415 Blue Spruce Dr., Fort Collins, Colorado, USA 80524

Abstract

Hot film probes and simple omnidirectional pressure sensors are commonly used to measure wind speeds near the surface in boundary layer wind tunnel studies designed to predict pedestrian level winds. Some practical limitations of using these wind speed measurements are discussed. A new omnidirectional 6-hole pressure probe designed for this purpose is introduced.

1 Introduction

When predicting wind speeds, the wind tunnel is expected to reproduce all wind speed changes lasting under an hour, including scales that are typically thought of as gusts. The larger scale changes in wind direction and speed are accounted for in the meteorological data. The manner in which the meteorological data and the wind tunnel results are combined is the subject of a companion paper [1].

In a second companion paper [2], the authors discuss the importance of measuring gust wind speeds in order to predict pedestrian comfort, and advocate the direct measurement of gust speeds from low-pass-filtered wind speed time series. This is in contrast to the common practice of inferring gust speeds using the standard deviation and mean of the wind speeds.

This paper addresses several issues with instrumentation that must be faced when performing pedestrian wind comfort studies. There are two primary methods currently in use for measuring wind speeds in a wind tunnel. The first is the use of hot-film or hot wire probes. The second is the use of Irwin pressure sensors. Both are discussed below. As a result of limitations of these devices, a new instrument, a six-hole surface mounted pressure probe, has been tested at CPP, and some preliminary results are presented.

2 Hot film sensors

Figure 1 includes an image of a "J-shaped" or 90° hot film probe typically used in pedestrian wind studies. Behind the heated wire is a metal bar that connects to the top and bottom of the film. When the air flows in a direction where either the bar or the heated wire is in the other's wake, the cooling effect is reduced, and the probe underestimates the air speed, as shown by the measurements in Figure 2. To avoid errors greater than 10%, it is apparent that the probe should only be used if the flow direction remains within ± 30° of the calibration direction. There are two difficulties with this in practice:

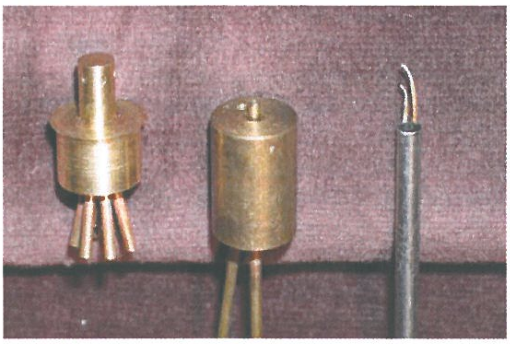

Figure 1: Sensors for measurement of pedestrian (surface) wind speeds in a wind tunnel. From left to right: a 6-hole probe, an Irwin sensor, and a "J" - shaped hot-film probe.

1. It is very difficult to predict in advance the direction of flow at a given location. It is also painstaking to keep the probe properly aligned as the approach flow wind direction changes.
2. Flow in wakes is inherently unsteady, with flow direction changes well in excess of ± 30°. Therefore, even if the probe is properly aligned with the mean flow direction, errors will be introduced. As we will see in Section 3, at locations of flow reattachment, the flow patterns are so unsteady that the mean flow direction is meaningless.

* Corresponding author. *Tel.:* +1-970-498-2350 *e-mail:* dbanks@cppwind.com

It might be countered that locations where the flow direction is unsteady are unlikely to see high enough wind speeds to cause pedestrian wind comfort problems, but measurements of low wind speeds near the ground can be necessary to ensure ventilation effectiveness and to assess whether the winds are mild enough for certain purposes, such as pool decks or outdoor terraces intended for receptions, or restaurants.

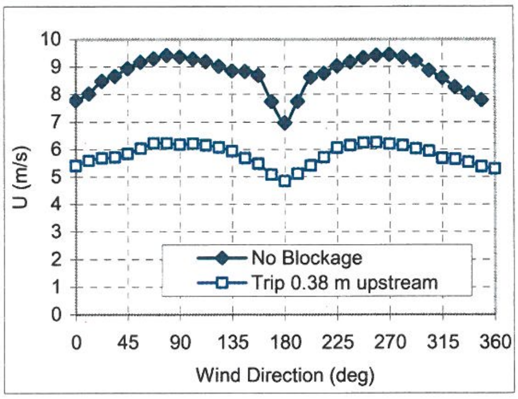

Figure 2: Effect of wind direction on wind speed measured by hot film. Film was calibrated with the support bar behind the heated wire.

3 Irwin sensors

3.1 Directionality

The Irwin surface wind sensor [3] uses the difference between the pressure in a well around the base of a tube (by convention called the static pressure) and the pressure at the top of the central tube (the dynamic pressure) to calculate the wind speed. A sensor is shown in Figure 1. The sensors were calibrated using the equation

$$U = \alpha + \beta\sqrt{\Delta P} \tag{1}$$

by comparing the velocities with velocities measured by a hot film probe in the same location in an open tunnel, with no models in place.

The Irwin sensor is considered omnidirectional. As with the hot film, it measures wind speeds, rather than velocity vectors, and its geometric symmetry should prevents the type of directional sensitivity seen for the hot film in Figure 2. Rotating the probes during calibration, however, revealed that some directional sensitivity was present in our sensors, as shown by the sinusoidal patterns in Figure 3. The behaviour was present both in sensors built to conform to the original design in [3] and in others built to match a revised design presented by Wu and Stathopoulos [4].

It is likely that this directionality is due to small asymmetries in the sensor construction. Although no such asymmetries were apparent when the probes were inspected visually under magnification, the sinusoidal patterns became more pronounced when the dynamic tube was pushed to one side, or when one side of the static tube as plugged with putty. Conversely, little effect was noted when filing one edge on the top of the dynamic tube, and there was no correlation between the sinusoidal pattern and the position of the static port in the well.

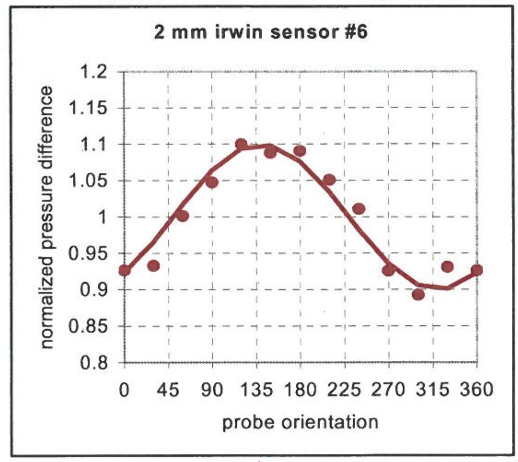

Figure 3: Irwin sensor directionality test results for a typical h = 2mm sensor. Results were repeatable in different tunnels, and at speed ranges from 6 m/s to 15 m/s.

Both h = 2 mm sensors (where h is the height of the dynamic tube) and h = 5mm sensors were tested, and the sinusoidal directionality was more pronounced for the shorter sensors.

This variability is roughly halved when calculating the speed with Equation (1), leaving a 10-15% swing in wind speed values with direction. This could be considered acceptable. However, care should be taken to avoid damaging the sensors, as destructive testing indicated that if the static port becomes dirty and plugged, or the dynamic tube is knocked and becomes tilted, errors of over 50% can be introduced due to the directional sensitivity. Since a visual inspection did not reveal any differences between sensors with a ±15% swing and those with a ±3% variability, the initial calibration procedure for these devices should include directional testing, since it is not clear whether or not a defect causing a ±25% error would be apparent.

3.2 *Calibration*

The expected values of α and β in Equation (1) for our experiments were 0.3 and 1.9 respectively for the h = 5 mm sensors, according to [4]. The values measured during calibrations varied considerably from these predictions in many situations. However, the nature of this variation was somewhat obscured by variation in the α term. Since this term ought to be close to 0 (given that ΔP will be 0 if $U = 0$), Equation (1) was re-arranged to yield

$$U = \beta\sqrt{\Delta P} = \sqrt{\frac{2}{R\rho}}\sqrt{\Delta P} \tag{2}$$

so that R is the fraction of the flow head that appears across the sensor,

$$R = \frac{\Delta P}{\frac{1}{2}\rho U^2} \tag{3}$$

A fit to the data of Figure 4 gave a value of R for our Irwin sensors of about 0.5 in smooth (Tu = 8%) flow. However, when 0.1 m by 0.1 m blocks were placed in the tunnel near the sensor (directly upwind, to the side, or forming a gap with the probe in the center), the R values were generally much higher.

There was some hope that the R values might be a function of turbulence intensity, but there is little evidence from these tests that this relationship can be used to correct the calibration.

The result of the increase in R in the wakes and shear zones near bluff bodies is that unless the probe has been calibrated in a similar flow, it will overpredict the speed, as shown in Figure 5. It is not clear at this time why the Irwin sensor's response changes with the flow situation, but the problem is repeatable over a range of realistic flow situations.

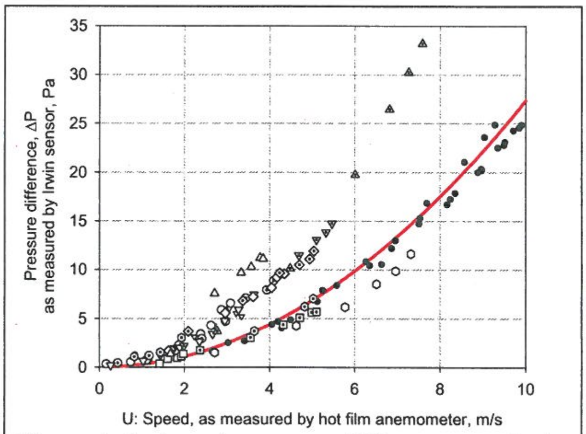

Figure 4: Irwin probe pressure difference vs. velocity measured with a hot wire. Filled circles indicate data taken in open tunnel calibration prior to each test with bluff bodies in the tunnel. Open symbols represent data taken at varying tunnel speeds, with different arrangement of bluff bodies.

4 The 6-hole probe

In light of these difficulties, a new 6-hole pressure probe for measuring surface velocities is being developed. The probe is shown in Figure 1. In order to house six holes, the probe is wider

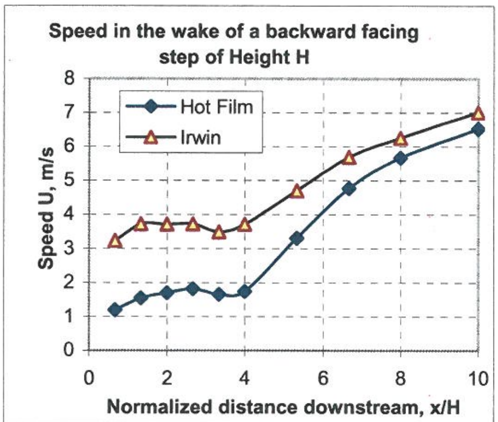

Figure 5: Mean velocity measured by Irwin sensor and hot film probe 5mm above the tunnel surface as a function of distance from the trailing edge of a backward-facing step that spans the tunnel. fps is feet per second.

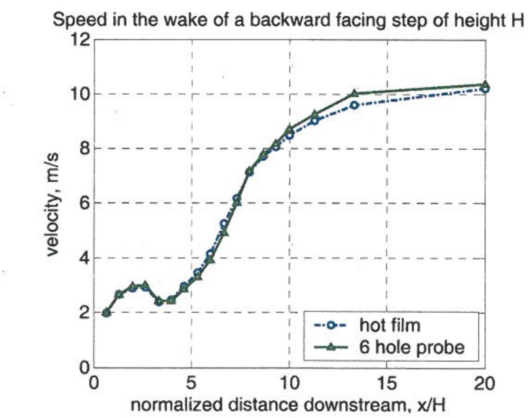

Figure 6: Comparison of speeds measured in the wake of a tunnel-wide, 10cm long, H = 4 cm tall trip which effectively forms a backward facing step.

(diameter = 5 mm) and taller (h = 6.5 mm) when compared with the Irwin probe (d = 1.6 mm, h = 5 mm). This will produce a larger probe wake. Both types of sensors should be separated by a minimum distance of about 10 d to avoid the wake velocity deficit.

Pressures are recorded simultaneously at each of the six evenly spaced holes or "taps" around the circumference of the cylindrical 6-hole probe. The probe uses the pressure difference between the stagnation on the windward side of the probe and the mean pressure in the wake of the probe to calculate wind speed. As with the Irwin probe, we expect ΔP to be 0 for U=0, so Equations (2) and (3) are used. The typical value of R from our wind tunnel tests is close to 1.0, or twice the signal of the Irwin probe.

At each time step, the tap with the highest pressure is located and compared with the pressures of the neighbouring taps, allowing the flow direction to be estimated. The pressure in the wake is assumed to be an average of 3 tap pressures. This average is then subtracted from the peak positive pressure to produce a total ΔP for use in calculating the velocity. The results are promising, as predicted velocities match those of the hot film along the wake of the backward facing step, as shown in Figure 6.

Figure 7 displays some detailed analysis of a single datum point from Figure 6. The point lies just inside the recirculation region behind the step (x/H = 3.3). It is interesting to note that the mean flow direction of around 30° has very little meaning, as the histogram on the right indicates that any wind direction between 0° and 60° is equally likely to occur, and that winds from outside this range are as likely as winds from inside this range. In this situation, aligning a hot film probe with the mean flow direction will not prevent the errors shown in Figure 2. In fact, to truly compare the two probes, the 6-hole wind direction data should be used to bias the 6-hole wind speed data with the directionality error of the hot film.

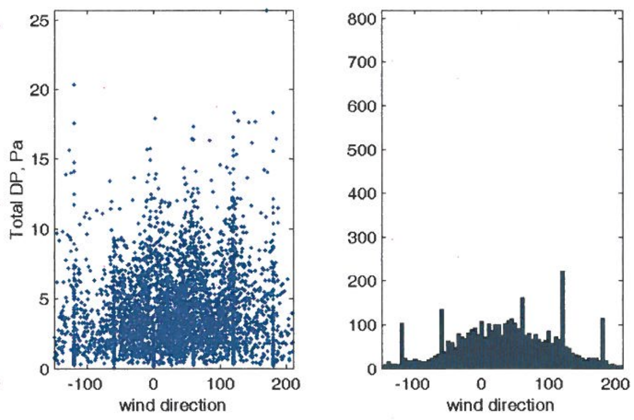

Figure 7: 6-hole probe data at a distance of x = 3.3H behind the backward facing step. This is close to the mean point of reattachment, at x = 4H. Flow from the step toward the probe is at 180° in this case, so that a wind direction of 0 degrees indicates flow reversal. Data on the right is a histogram, showing the counts at each direction.

Research into the probe continues. There is some evidence that the probe will under-predict velocities when placed directly upstream of an obstacle.

5 Conclusions and recommendations

Both the hot film and the Irwin sensor suffer from directionality swings in velocity of up to ±15% and ±8% respectively. In highly fluctuating flows, these errors cannot be compensated for by probe orientation, and the flow direction is too unsteady and unpredictable.

The Irwin sensors used in this study exhibited different calibration curves depending upon the flow situation in which they were placed. A new 6-hole probe is being tested which (so far) has a less situationally dependent calibration. The 6-hole probe also allows flow direction to be measured.

References

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