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Further experiments on Irwin's surface wind sensor

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Abstract

The simple surface wind sensor proposed by Irwin measures wind speeds through pressure differences. It has been applied in several wind-tunnel laboratories for the study of pedestrian-level wind conditions. However, some characteristics related to sensor performance for wind-tunnel measurements have not been fully investigated. Discussed in this paper are: calibration of the sensor for measuring mean and rms wind speeds, the effect of sensor height on measurement errors, the interference between nearby sensors, and the response of sensors to turbulent wind conditions. Data presented here supplement Irwin's original results on the surface wind sensor and provide additional insight in the performance of the sensor.

1. Introduction

In wind-tunnel experiments for determining the pedestrian-level wind speeds it is often required to make measurements at numerous locations, for various wind directions and at a low level near the ground. Traditional measuring techniques, such as Pitot tubes and thermal anemometers, are either inaccurate or inconvenient for these measurements. Therefore, an omnidirectional pressure sensor was proposed by Irwin [1] for the measurement of surface wind flows.

Fig. 1 shows the sensor of Irwin's original design with *standard* dimensions, and the sensor fabricated at the Building Aerodynamics Laboratory of the Centre for Building Studies in Concordia University, Montreal. Each sensor consists of two brass tubes and a mounting base. One of the tubes protrudes out of the base as a probe, while the other is connected with a circular hole on the base around the probe. Pressure differences between the inlets of the two tubes are outputs of the sensor. For the two sensors shown in Fig. 1, there are some slight differences in dimensions due to the availability of materials and the convenience of fabrication. The new sensor has a variable probe height ($h = 0$ to 5 mm)

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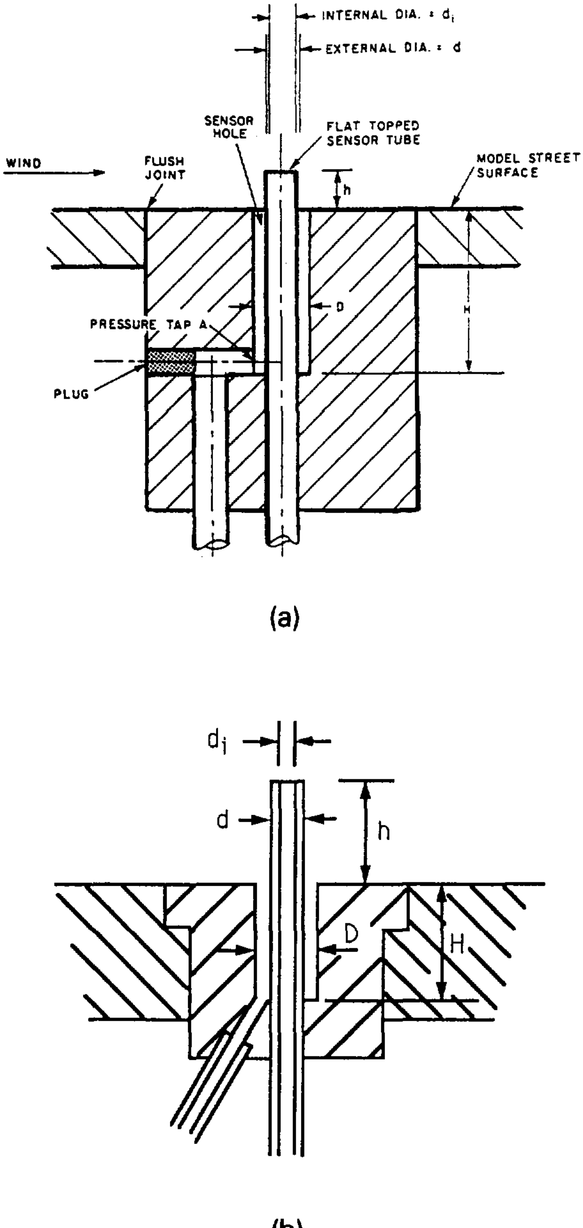

Fig. 1. Sketches of the surface wind sensors: (a) designed by Irwin (standard dimensions (mm): $d = 1.7$, $d_i = 1.2$, $h = 1.7$, $D = 2.6$, $H = 5.1$), and (b) reproduced in the current study (dimensions (mm): $d = 1.7$, $d_i = 0.9$, $h = 0$ to 5.0, $D = 2.6$, $H = 5.1$).

for operative flexibility. It also has a more direct connection to the circular hole on the base around the protruded probe, since a right angle in Fig. 1a is usually undesirable for the transmission of pressure signals.

The sensor has been proven satisfactory for routine tests of wind environmental conditions. Durgin [2] tested geometrically similar sensors in the Wright Brothers wind tunnel and found comparable calibration constants with Irwin's data. Williams and Wardlaw [3] fabricated, tested and installed as many as 615 such sensors with the city model of Ottawa for wind environment evaluations. However, other laboratories are more hesitant in the utilization of the Irwin sensor, perhaps because some features of the sensor important for the measurement of turbulent wind flows around buildings at the ground level have not been very clear. For example, the sensor is usually calibrated in a wind tunnel without the presence of any building models; what is the reliability of the sensor for measuring the flow near buildings when wind flows from different directions have high turbulence intensities? Another issue relates to the sensor height. According to Irwin [1], a short sensor ($h = 1.65$ mm) could be used to detect the wind speed at a higher level ($h_s = 3.75$ mm). Is this valid for any wind conditions? In other words, what should be the appropriate sensor height for a given level of wind speeds? When a higher sensor is selected, say $h = h_s = 5$ mm, the potential interference between sensors and the disturbance of the air flow due to the sensor has to be taken into consideration. However, only results of the along-wind interference for two short sensors with $h = d = 1.65$ mm were presented in Irwin's original work. Regarding the turbulence response of the sensor, a certain discrepancy was found by Irwin. This may vary with sensor configurations and the experimental environment and has to be carefully examined. Answers to such questions were sought in the authors' laboratory prior to the course of considering the sensor for pedestrian wind studies. The material presented in this paper serves as a supplement to Irwin's original work.

2. Review of Irwin's work and discussion

The pressure difference Δp of the sensor can be related to the wind speed Q at a chosen height (h_s). A simplified instantaneous relation was given by Irwin [1]

$$Q = A\frac{v}{h} + B\sqrt{\Delta p/\rho} = \alpha + \beta\sqrt{\Delta p}\,, \tag{1}$$

where h is the height of the sensor probe, ρ and v are the density and kinematic viscosity of air flow, A, B, α and β are constants depending upon flow characteristics, sensor dimensions, measuring height and other parameters.

Denoting mean values by $\overline{\Delta p}$ and $\bar{Q}$ and fluctuations about the means by $\Delta p'$ and Q', the relations for mean and rms are also given as

$$\bar{Q} = \alpha + \beta[\overline{\Delta p} - \frac{1}{4}(\overline{\Delta p'^2}/\overline{\Delta p})]^{1/2}\,, \tag{2}$$

$$(\overline{Q'^2})^{1/2} = (\beta/2)[\overline{\Delta p'^2}/\overline{\Delta p}]^{1/2}\,. \tag{3}$$

Note that Eqs. (2) and (3) are not exact deductions from Eq. (1) since high order terms in the Taylor expansions have been truncated. This approximation may be one of the causes for higher turbulence readings taken by the sensor than the hot film (about 10% on average) as found by Irwin. Moreover, when the mean and rms values of the differential pressure have similar magnitudes, the approximation may induce considerable difference from the exact solution. Although this thought deserves further examination from a mathematical viewpoint, the matter remains open for three reasons: first, such conditions only happen in zones with relatively low wind speeds that are not of the most interest in the pedestrian-wind studies; second, the accuracy of the thermal anemometer used for calibration is also found questionable for wind flow with high turbulence intensities; and third, the time history of Δp can be converted directly to instantaneous wind speeds using Eq. (1), thus avoiding the need of Eqs. (2) and (3).

Tests carried out by Irwin [1] were mainly for the *standard* sensor whose dimensions were specified in Fig. 1a. They dealt with sensor calibration, response to fluctuating flow, sensitivity, mutual interference, application limits, etc. Some conclusions of that study may be summarized as follows: (1) the device is capable of measuring the mean wind speed and the low-frequency fluctuations for wind speeds higher than 3 m/s, (2) sensor sensitivity increases with the sensor height h, (3) the value $d_i/d = 0.72$ is likely near the optimum for maximum sensitivity, (4) there is little to be gained by departing the tube top from the simple flat shape, and (5) the most critical case for interference between two sensors is when one sensor is directly upwind of the other with distances less than $12d$.

Additional comments on Irwin's results will be made to relevant sections of this paper.

3. Experimental environment

The detailed investigation on the sensor was carried out in the Building Aerodynamics Laboratory of the Centre for Building Studies, Concordia University. The laboratory is equipped with a boundary-layer wind tunnel [4] with a working section of 1.8 m × 1.8 m and a length of 13 m. The gradient wind speed in the wind tunnel can be controlled from 4.5 to 13 m/s when a suburban exposure is simulated. The turbulence intensity is maximum near the ground with a value higher than 20% and reduces to about 5% at the gradient height level. Based on simulation criteria a geometric scale of 1/400 is considered appropriate for modelling of wind flow conditions around buildings and other structures.

A Scanivalve system employed in the current study is equipped with Setra-237 transducers in the range of ± 0.1 psid. Plastic tubing is used to connect transducers and sensors. Several tubing configurations have been attempted. The final selection is made for a 50 cm long plastic tube with a restrictor in the middle. This tubing combination is capable of providing a flat frequency response up to 100 Hz. Beyond that, the signal response will be gradually attenuated. All signals are filtered by a low-pass filter set at 100 Hz and discretized at a rate of 256 samples/s.

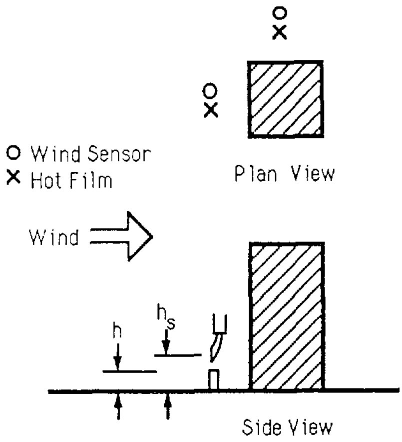

Fig. 2. Arrangement of hot-film anemometer and surface wind sensor in wind tunnel with a model building.

Results reported in this paper are for the sensors with the dimensions shown in Fig. 1b. The sensor height is adjusted at 5 mm (2 m in full scale) except in Section 4, where the influence of sensor height is examined.

4. Effect of sensor height

A small size sensor is desired for scaled model tests in order to reduce both the interference between sensors and the disturbance of the sensor to air flow. According to Irwin [1], a short sensor can be used to measure the wind flow at a higher level, i.e., $h_s > h$. Experiments have been made to examine this suggestion.

The experimental set-up is sketched in Fig. 2. To monitor the horizontal components of wind speeds, a hot film is installed vertically with the middle point of the filament at 5 mm above the tunnel floor, i.e., $h_s = 5$ mm. The pressure sensor with the variable height is set at $h = 2$, 4 and 5 mm. The two devices are placed so closely that the difference caused by their locations may be disregarded. A building model involved in the test has a full-scale equivalent height of 60 m and a square cross section of 30 m. Measurements are taken at full-scale equivalent 15 m in front of the building model and 10 m from the building side face. These two positions correspond to the windiest locations caused by the front vortex and corner streams around the building.

Eq. (2) could be rewritten as

$$\bar{Q} = \alpha + \beta P, \quad \text{where} \quad P = [\overline{\Delta p} - \tfrac{1}{4}(\overline{\Delta p'^2}/\overline{\Delta p})]^{1/2}. \tag{4}$$

Fig. 3 presents comparison results under a range of wind speeds for different sensor heights. The ordinate in the figure is the mean wind speed $\bar{Q}$ measured by the hot film in m/s and the abscissa represents the P value detected by the sensor in $\mathrm{Pa}^{1/2}$. Data at

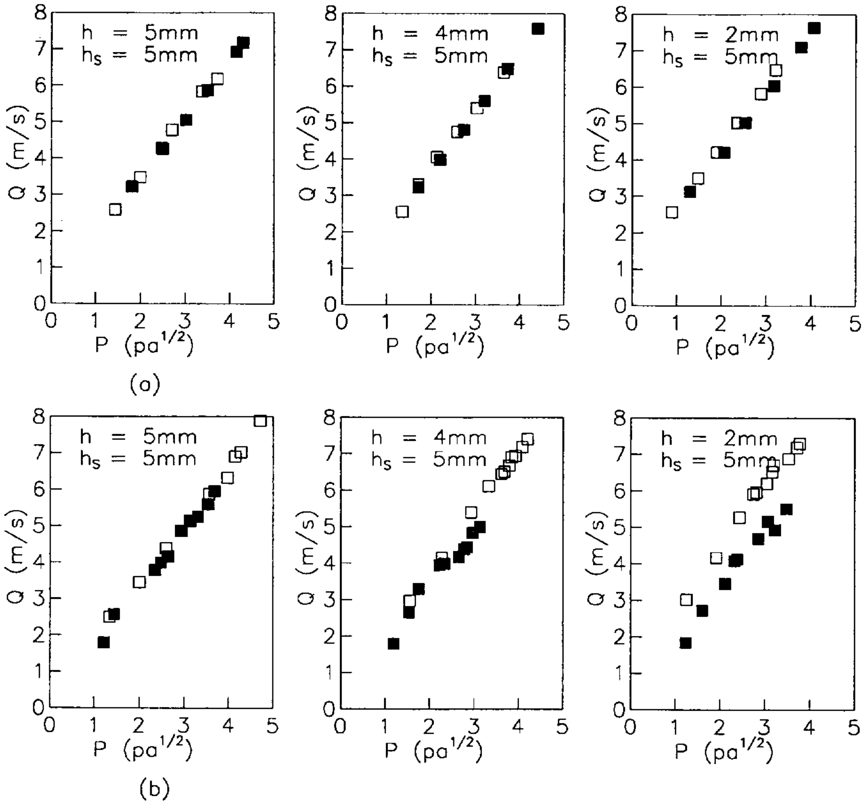

Fig. 3. Variations of P values with the mean wind speeds $\bar{Q}$ measured by hot-film anemometer: (a) corner streams, and (b) front vortex (■ with and □ without buildings).

same locations when the building is absent are compared in the figure. For the corner streams shown in Fig. 3a, the pressure value varies with the wind speed following the same linear relation despite the building presence, even for the sensor of 2 mm high while the hot film stays at 5 mm. Moreover, when a sensor with a 5 mm height is used to measure the front wind speeds at 5 mm above the floor, its outputs are also similar with or without the building. A deviation, however, can be observed in Fig. 3b when the sensor is placed at different height from that of the hot film and this is especially evident for the 2 mm sensor. This discrepancy simply indicates that when the sensor and the hot film are not at the same level there is no single relationship between their outputs in the presence or absence of the building under consideration. The existence of a single linear relation between P and $\bar{Q}$ is a necessary condition for the calibration of sensors in order to measure flow speeds under various wind conditions around different building models. It appears that the sensor, calibrated under conditions of idealized flows with uniform roughness without any buildings around, is capable of measuring building-induced winds at the same height, even in the building front where

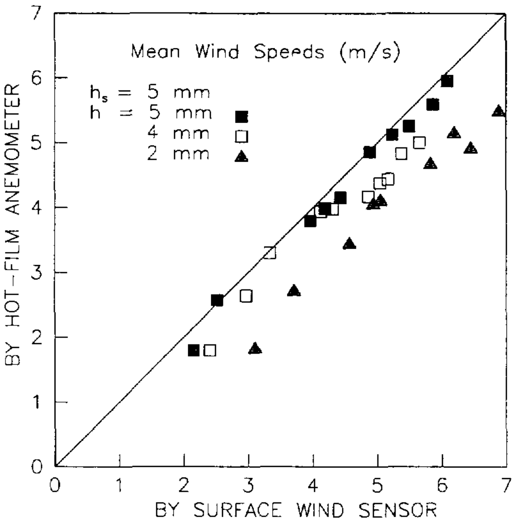

Fig. 4. Comparison of wind speeds in front of a building, measured by surface wind sensors at different heights and hot-film anemometer at 5 mm above the ground.

downwash vortex exists. However, a sensor with a certain height generally cannot be used to measure the wind speed at a higher level.

This observation is further illustrated in Fig. 4 drawn from the data of Fig. 3b for the front vortex. Wind speeds in front of the building are calculated for the sensor from the calibration constants derived for each sensor-hot film combination without the building in place. The data of 5 mm sensor are the most accurate comparing with the hot-film measurements (data points along the 45 degree line) while lower sensors clearly overestimate the values of wind speeds. This phenomenon is possible due to the small turbulence eddies in boundary layer flow and the variation of surface characteristics introduced by the building. Consequently, it is suggested that the sensor be set at the height of the wind speed of interest for a reliable measurement. In the following tests, the sensors' height has been adjusted at 5 mm to measure the wind speed at 2 m in full scale.

5. Interference between sensors

A comprehensive assessment of ground wind flows requires several sensors closely spaced around buildings. For high sensitivity to pressure signals, a sensor with relatively large dimensions is preferred. In order to inspect the potential interference between sensors, a dummy sensor is made at the same size with the actual one and placed together in the wind tunnel. As in Irwin's study, only the mean pressure difference is recorded by the measuring sensor when the dummy sensor is put at a nearby location. The interference induced by the dummy sensor at corresponding

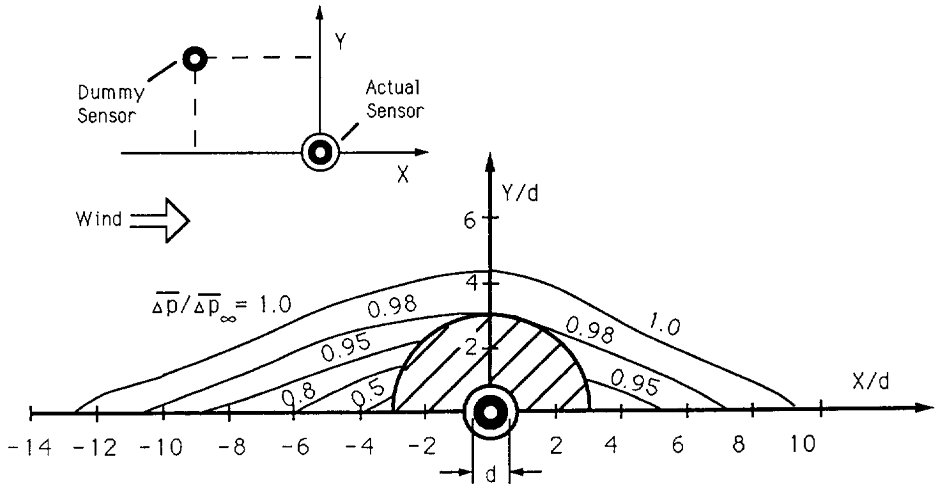

Fig. 5. Interference between two identical sensors with a height of 5 mm.

locations is represented by contours of the ratio of mean pressure difference $\overline{\Delta p}$ when the dummy sensor is present to that of an infinite separation $\overline{\Delta p_\infty}$. Results are shown in Fig. 5 and distances between sensors are normalized by the sensor diameter. It is interesting to note that the presence of an influencing sensor always reduces the mean pressure difference on the measuring sensor. For instance, if the influencing sensor is 6*d* upstream of the measuring sensor, the latter will have a pressure difference 20% lower than that of an isolated sensor under the same wind condition.

The most critical interference condition is when the dummy sensor is directly upwind of the actual sensor. In this case, the interaction effect becomes noticeable for distances between sensors less than 12 times the sensor diameter, i.e., about 2 cm for the 1.6 mm diameter sensor. This is similar to the spatial extent of interference found by Irwin [1] although the sensor height is about 3 times higher than that used by Irwin. This indicates that the sensor diameter, rather than the height, plays a dominant role in disturbing the wind flow passing around. Regarding lateral disturbance, a distance of five diameters for two side-by-side sensors will be sufficient to cancel the mutual interference. Finally, the influence from a downwind sensor is much less significant than that from an upstream one.

6. Response to turbulence

Wind gust is also important to the evaluation of environmental conditions. Fig. 6 shows time histories of wind speeds recorded simultaneously by a hot-film anemometer and a sensor around the corner of a building as shown in Fig. 2. The signals generally match each other. Slight time shifts or phase lags between two signals can be found during some short time intervals, which may be related to the overall

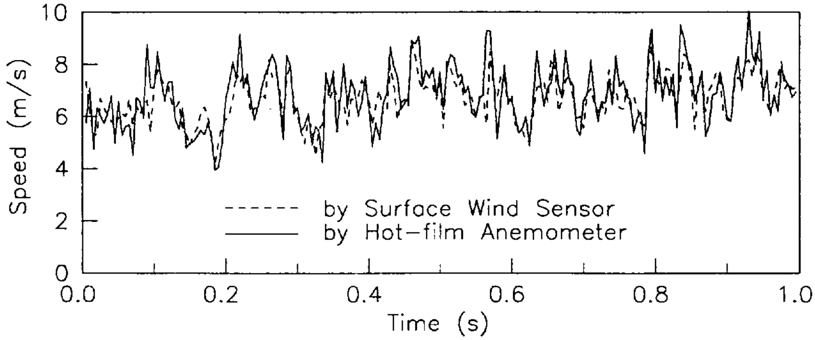

Fig. 6. Time histories of the same speed record measured simultaneously by hot-film anemometer and surface wind sensor.

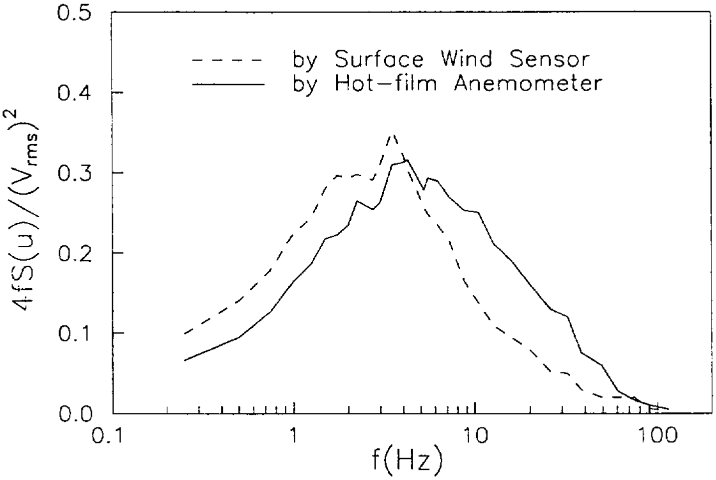

Fig. 7. Wind power spectra calculated from measurements of hot-film anemometer and surface wind sensor.

characteristics of the sensor-tubing-transducer-Scanivalve system. The correlation of the two signals is not as good as that obtained by Irwin, but no "sudden excursions to very low Q values in the sensor data" [1] have pronouncedly been observed in the current experiments.

The time histories may be analyzed and presented in the form of coherence or spectrum. Irwin [1] studied the coherence functions and suggested a good similarity between the two signals on the low frequency part. However, different results have been found in this study by comparing the wind spectra measured by the hot-film and the sensor.

The sensor's signal depicts the wind fluctuation at the top opening, and the low-frequency turbulence around the bottom of the probe. Fig. 7 shows spectra of the velocity signal measured by the pressure sensor and the hot film. Clearly, the spectrum measured by the sensor contains more low-frequency energy than that by hot film anemometer. This may be due to the following two reasons: (1) low-frequency flow fluctuations below the measuring height are captured by the hole on the sensor base, and (2) the sensor may also be influenced by vertical flow fluctuations, whereas only horizontal flows are sensed by the hot-film anemometer. It may become another error source of the overestimation of rms wind speeds if low-pass filters are used for both the hot film and the sensor.

In addition to the background turbulence, fluctuations in the current measuring system may be attributed to other sources. Owing to the small dimension of the sensor, the flow separation from the top and the sides of the probe body is expected to generate high-frequency fluctuations; this is not critical for pedestrian-level wind studies and can be filtered out by a low-pass filter if necessary. Electric noise that is insignificant for hot-film signals may become more pronounced and needs special consideration for the sensor because the voltage of its signal is extremely low.

7. Calibration based on mean speeds measured by thermal anemometers

As reported in Irwin's paper [1], the sensor was calibrated in a simulated turbulent boundary layer first for the relationship of the surface friction coefficient measured by a Preston tube and the pressure difference output by the sensor. Then, using the universal wall-law, a curve of the pressure difference versus the wind speed at a chosen height was established, as expressed by Eq. (1).

This process may be tedious and unnecessary for one who is interested only in applying the sensor for speed measurements. A more straightforward approach is to record the pressure difference for a range of wind speeds measured by a nearby thermal anemometer, and then use Eq. (2) to assign values to α and β by statistical analysis, e.g., linear regression. The rms wind speeds can be evaluated by Eq. (3) with known β and pressure values.

Another more comprehensive approach to establish the calibration coefficients involves a building model. The pressure sensor and a hot-film anemometer are positioned closely in the wind tunnel at a height of 5 mm. A high-rise building model is moved around so that wind speeds at the front, corner and wake area around the building will be measured by the two probes. Only a single wind-tunnel speed is required in this process. The sensor readings are recorded and calibrated against the hot film data. Such calibration results are shown in Fig. 8. The graph for mean wind speeds exhibits a high correlation between measurement results, while data for rms speeds are somewhat scattered. The correlation coefficients are found to be 0.98 and 0.90 for mean and rms wind speeds, respectively. This approach may compromise the performance of sensors at different locations around buildings and provide more reliable data in the average sense.

Based on the results of the present study for the 5 mm high sensor, constants in Eqs. (1)–(3) have been determined as

$$\alpha = 0.28, \quad \beta = 1.59 \quad \text{or} \quad A = 93, \quad B = 1.76,$$

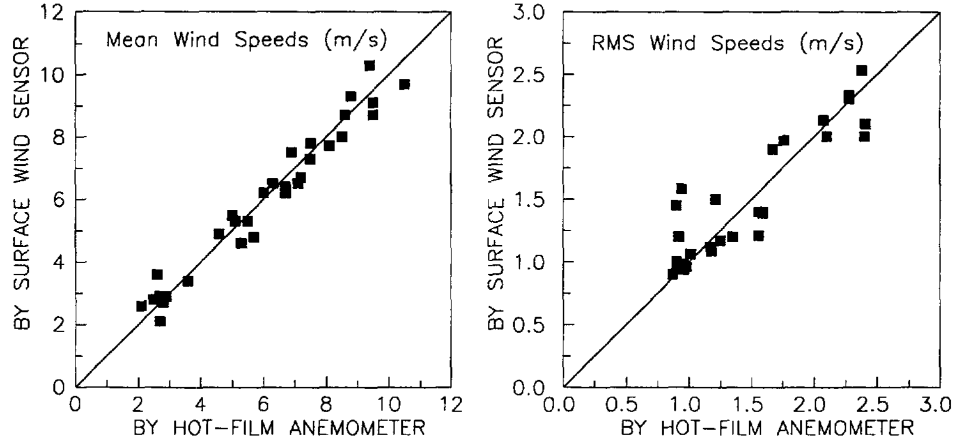

Fig. 8. Calibration of a single sensor at various positions around a model building.

Table 1
Comparison of calibration constants

References	A	B	Sensor dimensions (mm)
[1]	85	1.74	$h = d = 1.65$, $h_s = 1.65$
	110	1.91	$h = d = 1.65$, $h_s = 3.75$
[2]	92	1.71	$h = d = 1.65$, $h_s = 1.65$
Current Study	93	1.76	$h = 5$, $d = 1.65$, $h_s = 5$
	104	1.81	$h = 4$, $d = 1.65$, $h_s = 5$
	134	1.84	$h = 2$, $d = 1.65$, $h_s = 5$

when the mean and the rms speeds are in m/s and the pressure difference in Pa. These constants have been compared with values obtained by Irwin [1] and Durgin [2] and results are shown in Table 1. For comparison purposes, calibration constants have also been calculated from the data in Fig. 3 for sensors with different heights ($h = 2$ and 4 mm), although these cases are not suggested for reliable measurements. The simple approaches applied in the current study yield comparable coefficients with Irwin's original data. In general, results show that for $h_s/h = 1$, A is in the range of 85 to 93, and B varies from 1.71 to 1.76. The discrepancy is due to the difference in sensor dimensions, measuring height and particular wind conditions. In view of other uncertainties involved in the pedestrian-level wind studies, such differences are considered insignificant.

8. Concluding remarks

Experiments have been carried out to examine some features important for the performance of the surface wind sensor proposed by Irwin [1]. The major findings, considered as useful supplements to Irwin's original work, are as follows:

(1) The sensor should be set at the same height as the measuring level of the wind speed for a reliable measurement; considerable errors have been found when a short sensor is used to measure the wind flow at a higher level above the ground.

(2) The surface wind sensor detects wind fluctuations through its two pressure inlets. In comparison with the thermal anemometer, the sensor may overestimate low-frequency fluctuations of wind flows at the measurement level, since the inlet on the base captures the wind signals below the sensor height where low-frequency turbulence exists.

(3) The spatial extent of the interference between sensors could be estimated as functions of the diameter of sensors. The longitudinal and lateral extents of disturbance are found to be twelve and five times the sensor diameter, respectively.

(4) Two simple procedures implemented in the present study yield calibration coefficients comparable with Irwin's original data.

The sensor is a competent tool for pedestrian wind measurements. Note that only the horizontal component of wind speeds has direct effects on pedestrians. Reliable mean and rms speeds could be provided by the sensor if a careful calibration is performed. Furthermore, results of wind tunnel tests are usually presented as amplification ratios, so that any absolute errors of measurements can be lessened to a considerable degree. High turbulence intensity may also be a source of error in measurements by hot-film anemometer and other instruments, so it is hard to evaluate the sensor only from the comparison with the vertical hot-film data.

Acknowledgement

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