Developing a Static Pressure Reference Probe

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1. Introduction

Wind loads on cladding and façade elements depend on the pressure difference across the element. It is therefore critical to study the fluctuation of internal pressure relative to the external pressure to determine the correct wind load. A full-scale study is being conducted at The Hong Kong University of Science and Technology (HKUST) using a series of differential pressure sensors to measure pressure variations under strong wind conditions. These sensors are referenced to the ambient atmospheric pressure to optimize their functional range. The need to accurately measure the ambient atmospheric pressure is also important to investigate internal pressure phenomena that are closely related to the behavior of a Helmholtz resonator and which is affected by the state of the atmosphere[1].

A corner apartment located on the 7th floor of the Visitor Centre within the HKUST Campus has been chosen as the test site due to its relatively uninterrupted exposure to the prevailing monsoonal winds, thunderstorms and typhoons that affect the region. There are limited choices for locating an ambient atmospheric pressure probe to avoid distortion from surrounding features near the test apartment, and the suitability of these choices may be further limited by the penalty on pressure signal distortion and phase lag if a long tubing system is used to connect with remote sites.

In previous similar studies, reference probes have been located in a manhole on flat ground[2]. However, this is not particularly suitable for the current study due to the surrounding complex terrain and the substantial height (30m) of the test building above the adjacent ground level, making the building roof a potentially better option. A 6m high mast was set up on top of the roof to support the reference pressure probe and an anemometer (**Figure 1**). The probe is required to extract the dynamic pressure from the total pressure within an accuracy of 20Pa, to be manufactured from reasonably light, weather proof material and to be maintenance free.

Figure 1 - The Mast on the Roof of Tower C, HKUST

2. Background

The challenge of developing a suitable ambient pressure probe can be appreciated by looking into the United States Patent Database and the efforts of various inventors over the last century. Knisley[3] attempted to measure the static pressure in a unidirectional flow with a sleeved static tube by subtracting the dynamic pressure from the total pressure measured. The patent of Anderson[4] involved measuring the pressure inside a symmetrical porous probe and correlated the measured pressure with the static pressure by means of calibrations. Marshall[5] presented a design for an ambient pressure probe equipped with an adjustable shroud that could directly measure the ambient static pressure in an omindirectional flow . Moran and Hoxey[6] developed a probe similar to Marshall's[5], but with an additional collar, and tested the probe at different gap widths and over a range of pitch angles. Nishiyama and Bedard[7] developed a quad disk static pressure probe with two pairs of dishes that is able to measure flows from various pitch angles.

3.Theory

The total wind-induced pressure experienced by a bluff body can be conveniently divided into static pressure, caused by the Brownian motion of gas molecules which is a function of the state of the gas, and the dynamic pressure, which is due to the bulk momentum of the wind flow and which is a vector. The simplest method of segregating the dynamic portion from the total pressure is to align the face of the pressure tapping parallel to the direction of flow such that the cross product of the momentum vector of the flow with the face normal vector of the tapping becomes zero.

A unidirectional device pointed directly into the flow would be ample to perform the task in a steady flow field, but the flow in the atmospheric boundary layer is unsteady due to the nature of weather systems and the turbulence of the wind flow. While attempts have previously been made to mount a unidirectional device on a vane[8] to keep the tapping perpendicular to the predominant flow direction, the changes in flow direction due to turbulence make tracking the flow direction a formidable challenge.

To overcome the problems detailed above, a new device was designed in which the approaching wind flow was “trained” to keep it perpendicular to the tapping. The merit of this method is that the design is free from any moving parts, which is advantageous for maintenance. The major drawback is that the probe will generate its own pressure field in flows with large pitch angles which would distort the measurements. Ideally, a balance needs to be achieved between the amount of flow training and any pressure distortion by means of varying the gap width of the device, thereby optimizing the probe accuracy within the expected range of angle of attack for a specific application.

4. Configuration

The design adopted for this project is illustrated in **Figure 2**. A number of aluminum disks, with small holes drilled near the central hole, are separated by acrylic rings which act as spacers to control the gap width. The large and small acrylic rings are arranged in a staggered manner to create a central chamber that allows the pressure inside the chamber to communicate with the external atmosphere via holes drilled on the aluminum disks. The central chamber is capped by an aluminum cap mounted with an air tight plug to connect the tubing to a pressure transducer. The top plate was enlarged with a drop groove to provide rain shielding for the probe. Multiple layers of disk were stacked to provide redundancy in case of blockage by insects or debris. The whole setup is tightened with a tapered stainless steel screw and sealed with glue.

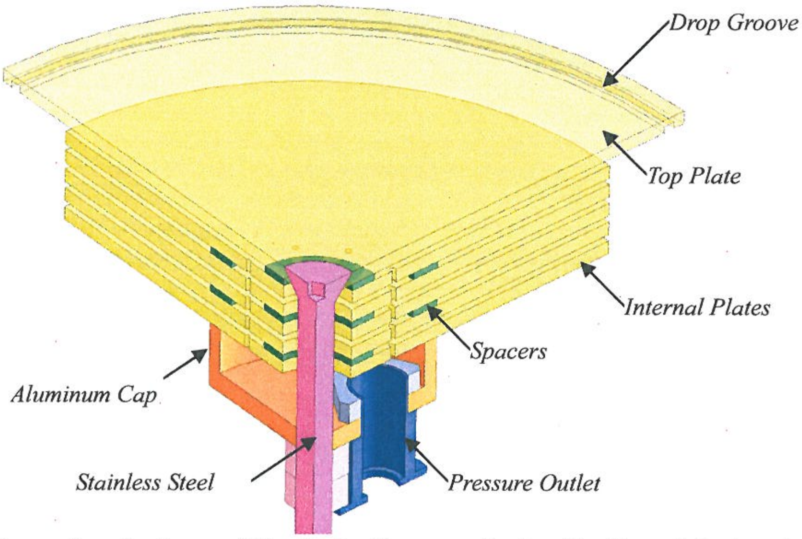

Figure 2 – Sections of the Static Pressure Probe, the Top plate is set transparent to illustrate the location of the holes on internal plate. Internal plate is separated by small and large separator rings in a staggered manner to crate an internal chamber which connected with the external.

The flow approaching the probe is trained by the aluminum disks and remains perpendicular to the drilled holes which act as pressure tappings. The central chamber acts as a manifold and hence the signal measured by a pressure transducer is a pneumatically averaged air pressure.

5. Characterization Tests

The probe was tested in the high speed boundary layer wind tunnel test section at the CLP Power Wind/Wave Tunnel Facility at HKUST. The probe was placed adjacent to a pitot tube mounted inside the high speed test section. The probe and the static port of the pitot tube were connected to the measurement ports of two individual differential pressure sensors. The reference ports of these transducers were connected to a stable reference environment via a manifold as illustrated in **Figure 3**. The pressure inside the wind tunnel is less than that of the reference environment and turbulent flow was generated by the inclusion of roughness elements and a fence mounted on the wind tunnel floor (**Figure 4**). The probe was tested in flows with turbulence intensities of approximately 10% and 15% and with mean wind speeds ranging from 5 m/s to 25 m/s. The probe was also tested at angles of attack ranging from +15° to -30°.

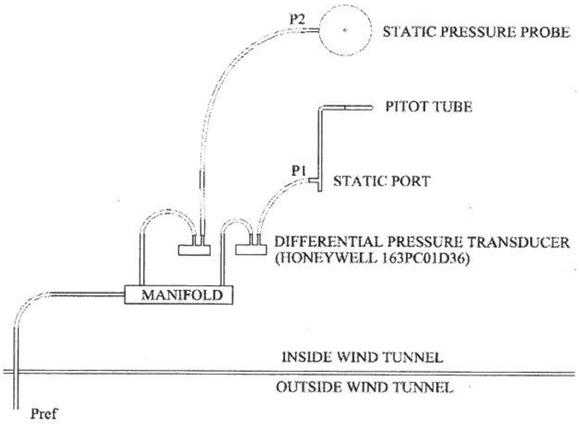

Figure 3 – Illustration of Testing Setup

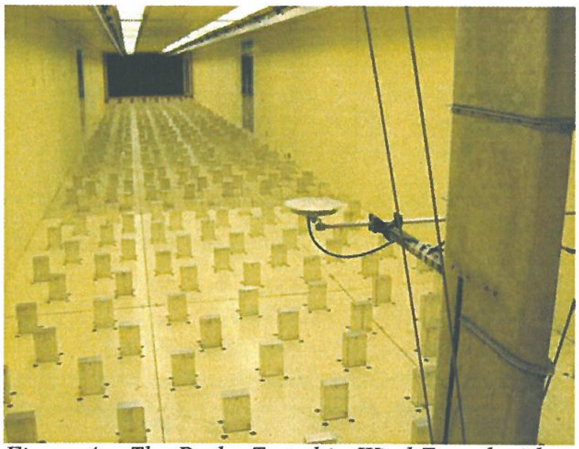

Figure 4 – The Probe Tested in Wind Tunnel with Roughness Elements mounted on floor.

6. Results

DC voltage signals from the differential pressure transducers were first amplified by a signal conditioning unit set at a low pass filter frequency of 30 Hz to attenuate electronic noise with a characteristic frequency of 50 Hz. The signal was then digitized using a 16-bit Analog-to-Digital system and stored on hard disk. The means of the measured pressure time histories were calculated for different angles of attack and wind speeds and subsequent comparisons were made between the probe and static port of the pitot tube as a percentage error (P_{err}%) defined in **Equation (1).**

$$\Delta P_1 = P_1 - P_{ref}$$

$$\Delta P_2 = P_2 - P_{ref}$$

$$\Delta P = \overline{\Delta P_2} - \overline{\Delta P_1}$$

$$P_{err}\ \% = \frac{\overline{\Delta P_1} - \overline{\Delta P_2}}{\overline{\Delta P_1}} x100\ \% \qquad (1)$$

P_1= Pressure Measured by the Static Port of Pitot Tube
P_2= Pressure Measured by Static Pressure Probe
P_{ref}= Pressure Outside Wind Tunnel

The result of these tests are presented in **Figures 5** to **8** inclusive.

7. Discussion

The first prototype probe was made with compact disks separated by rings cut from vulcanized rubber sheets without the enlarged top plate. The design was subsequently replaced with custom manufactured aluminum plates and acrylic separators to provide a weather resistant design. The final probe weight is 0.45kg with material cost less than US$50.

The results presented in **Figure 5** to **8** showed that the performance of the probe was relatively insensitive to variations in turbulence intensity. However, at large positive angles of attack, the differences between the probe and pitot tube static pressures are significantly larger than those for the corresponding negative angle of attack. This was not observed in the initial prototype and it is attributed to the presence of the enlarged top plate, which acts as an upwind obstacle at large positive angles of attack and subsequently generates a distorted pressure field around the probe. The effects of the top plate could possibly be overcome by tuning the size of the gap and/or shrinking the diameter of the top plate to suit different site conditions and purposes.

8. Acknowledgements

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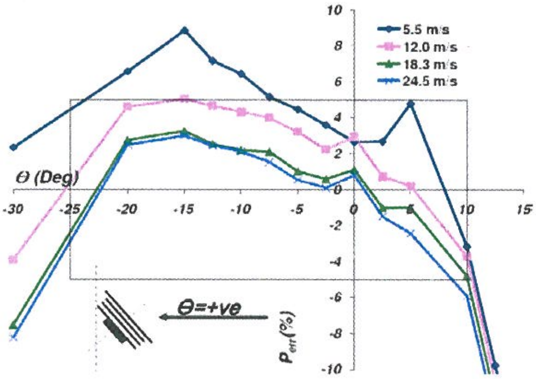

Figure 5 – Results Presented in Percentage Error, Separator Thickness = 1mm; I_{uu}=10%; Target Performance Range Marked within the Box.

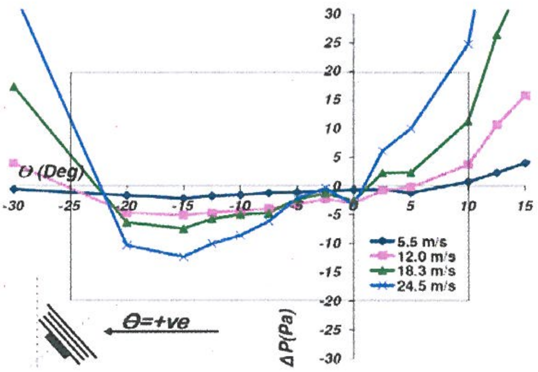

Figure 6 – Results Presented in Absolute Different, Separator Thickness = 1mm; I_{uu}=10%; Target Performance Range Marked with in the Box.

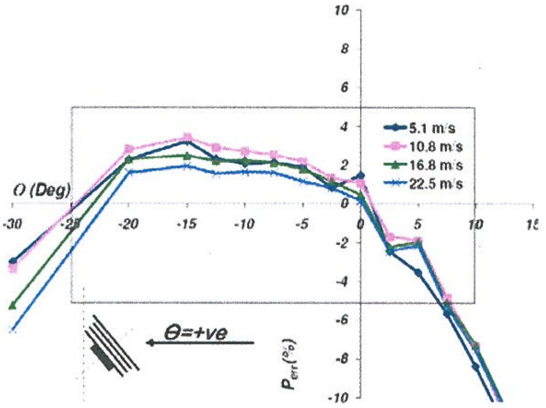

Figure 7 – Results Presented in Percentage Error, Separator Thickness = 1mm; I_{uu}=15%; Target Performance Range Marked with in the Box.

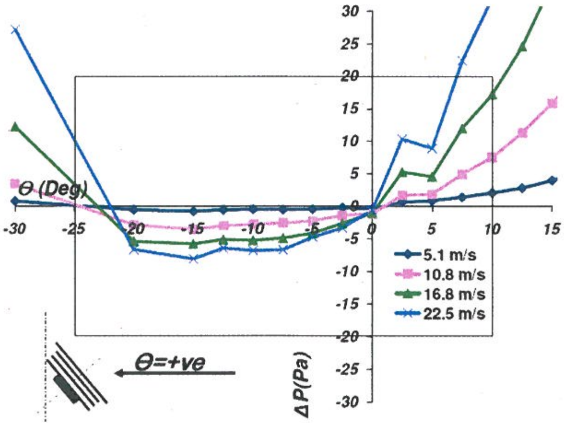

Figure 8 – Results Presented in Absolute Different, Separator Thickness = 1mm; I_{uu}=15%; Target Performance Range Marked with in the Box.

9. References

[1] Holmes, J.D. (1979), "Mean and Fluctuating Internal Pressures Induced by Wind", Proceedings, the 5th International Conference on Wind Engineering, Fort Collins, Colorado.
[2] Yeatts, B.B. (1992), "Internal Pressure for Buildings", MSc Thesis, Texas Tech University.
[3] Knisley, A.W. (1936), "Static Tube Sleeve", United States Patent Office, Patent No. 2101858.
[4] Anderson, G.F. (1962), "Omni-Directional Pressure Probe", United States Patent Office, Patent No. 3034353.
[5] Marshall, R.D. (1976), "Ambient Pressure Probe", United States Patent Office, Patent No. 3950995.
[6] Moran, P. and Hoxey R.P. (1979), "A probe for sensing static pressure in two-dimensional flow", J. Phys. E: Sci. Instrum., Vol. 12, pp752-753.
[7] Nishiyama, R.T. and Bedard Jr., A.J. (1989), "Quad Disk Static Pressure Probe", United States Patent Office, Patent No. 4838087.
[8] Holmes, J.D. (2005), private communications.