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Design and Performance of a Low-Cost Pitot Rake

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ABSTRACT
Seven-hole probes are a common and accurate way to measure the flow in wind tunnels. Unfortunately, these devices are expensive, require computationally expensive post-processing and are slow to collect data. Pitot rakes are a viable alternative to measure flow, provided that the angle between the direction of flow and the rake is small. The manufacture of a low-cost pitot rake will be outlined herein. It was made from easily available metal tubing and 3D printed components, costing a fraction of a standard seven-hole probe. It is shown, that the pitot rake is capable of taking similar measurements to the seven-hole probe at eight times the speed.
Keywords – Flow field, flow characterisation, pitot tubes, pitot rakes, wind tunnel

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I. INTRODUCTION

Flow measurement devices are an essential part of wind tunnel experiments, quantifying flow uniformity, turbulence, and pressure losses. Optical measurement techniques are often considered the gold standard of measurement devices, as they do not disturb the flow and produce accurate measurements. However, these techniques are often expensive and require expert knowledge to operate [1]. Therefore, traditional pitot tubes are still often employed, as they offer an inexpensive easy-to-use alternative.

Multi-hole probes are a more sophisticated version of the pitot tube. Using multiple holes to measure the flow, these devices are less sensitive to the flow angle and can measure individual velocity components, rather than just the velocity magnitude. While multi-hole probes are a useful tool, they are relatively expensive, due to stringent manufacturing and calibration requirements. Moreover, they acquire data only at a single point, meaning that the collection of data is comparatively slow.

The speed of data collection can be significantly increased through the use of pitot rakes. These devices are simply series of pitot tubes, allowing for measurements at multiple points simultaneously. The work herein outlines the design and manufacture of a low-cost pitot rake. While it does not match the accuracy or versatility of multi-hole probes, it is decidedly easier to use and accelerated data collection by a factor of eight. The performance of both the seven-hole probe and the pitot rake will be analysed in a critical side-by-side comparison.

II. MANUFACTURE OF THE PITOT RAKE

As shown in Fig. 1, the pitot rake features eight pitot tubes to measure the total pressure and one static pressure tube to measure the static pressure. These are all made from brass tubing which can be purchased cheaply at most model-making shops.

The tip of the static tube is sealed using epoxy and was carefully rounded using a file and sand paper after the resin had fully hardened. Four small static ports were drilled eight tube diameters downstream of the tip, following with the design recommendations of White [2].

A narrower pitot tube inlet significantly reduces noise in the data [3]. The openings were therefore narrowed by inserting smaller diameter tubes at the inlet. These were fixed in place using adhesive. The nose of each tube was then carefully rounded to resemble the hemispherical shape described by Ristić et al. [4].

The pressure tubes are held in place using a polylactic acid (PLA) plastic casing. The casing was 3D printed in halves, through fused filament fabrication (FFF) on a Creality Ender 6. The downstream and upstream halves were then joined with cyanoacrylate adhesive. The casing near the pitot tubes was streamlined to reduce flow disturbances. At the base of the rake, the casing is rounded to allow for easy mounting and rotation of the probe.

While the 3D printer should be accurate to ±0.1mm, plastic is easily deformed, thereby increasing tolerances. To counteract this issue, a small aluminium block was machined to hold the tubes in place with a higher degree of accuracy. It was attached to the casing by press-fitting it into a purpose-made recess.

The pitot tubes were placed eight tube diameters away from the static pressure tubes. The stem of a standard pressure tube is 16 tube diameters from the nose [5] [6]. As the aluminium block is significantly wider than the tube diameter, it was decided to extend this spacing to 23 tube diameters. The curvature of the tubes was set accurately by bending them around the shank of an M10 bolt. Unfortunately, the brass tubes come in a standard length of 305mm, thereby limiting the length of the plastic casing to 216mm.

III. MEASURING PRESSURE

Equation (1) shows how total pressure (p_t) is the sum of static pressure (p_s) and dynamic pressure (p_d):

$$p_t = p_s + p_d \tag{1}$$

To measure the pressures of the pitot rake, the brass individual brass tubes were connected to a digital pressure scanner. The scanner used herein was purchased from Surrey Sensors and was fitted with an 8-channel 1000 Pa pressure card. The accuracy of the card is ±0.25% of the range, i.e., ±2.5 Pa. This is equivalent to a flow velocity of ±1.6 m/s.

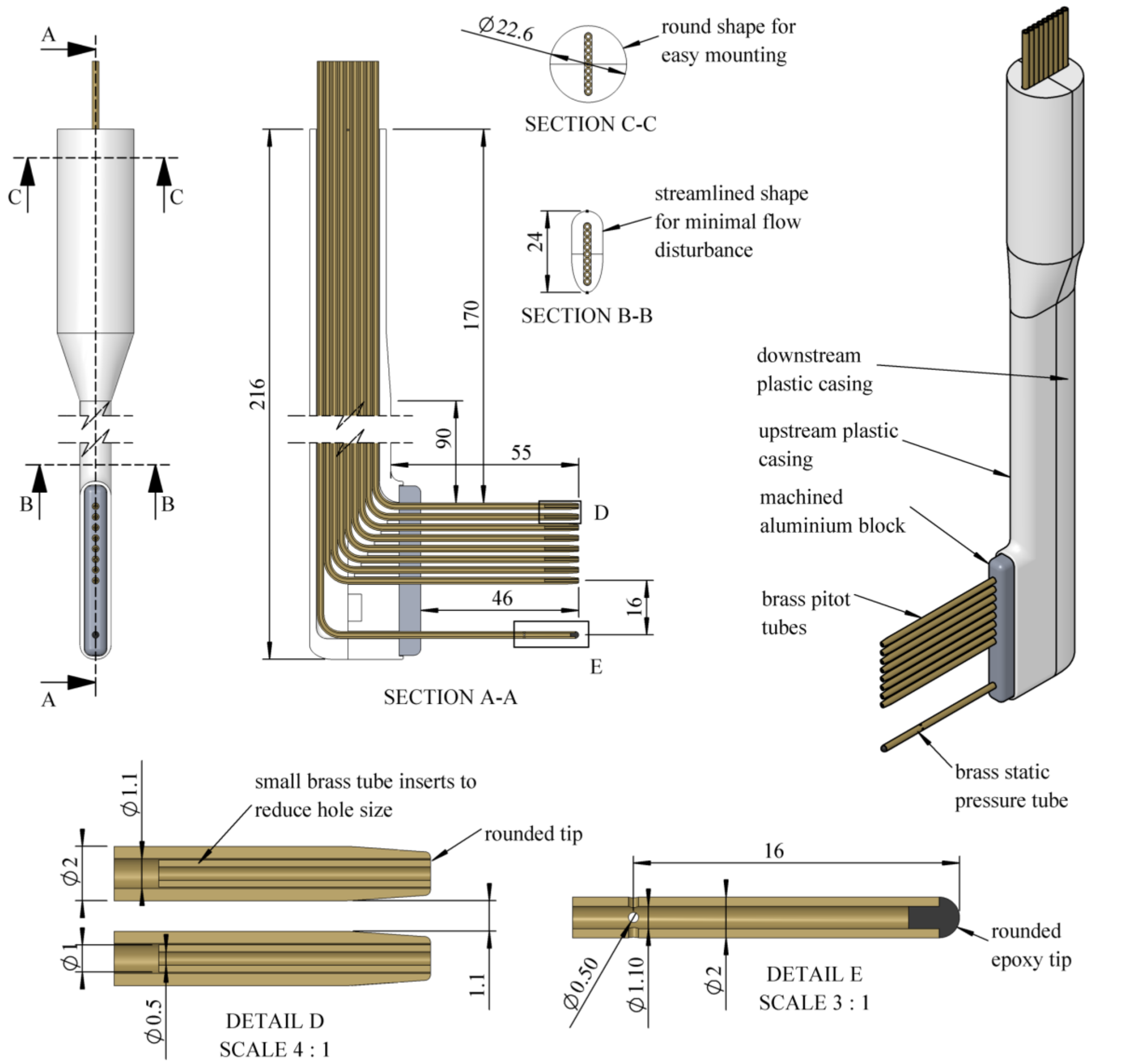

Fig. 1: Overview of pitot rake design and geometry. Unless otherwise specified, the scale is 1:2 and all dimensions are in millimetres.

Each pitot tube was connected to an individual channel, while the static pressure tube was connected as the reference pressure. As such, the pressure scanner gives direct readings of dynamic pressure. According to Bernoulli's Principle, the dynamic pressure and fluid density (ρ) are related to the velocity (u) through equation (2):

$$p_d = \frac{1}{2}\rho u^2 \qquad (2)$$

The performance of the pitot rake was tested against a pre-calibrated seven-hole probe, supplied by Surrey Sensors. As the company is a reputable supplier of the automotive industry, it is believed that their equipment is a good performance benchmark. The assembled pitot rake and seven-hole are shown in Fig. 2.

Fig. 2: Comparing the design of a seven-hole probe (left) and the pitot rake (right).

Both flow measurement devices were used to characterise the flow downstream of a vane cascade, shown in Fig. 3. This was deemed an appropriate test, as the flow field in this location is complex and highly 3-dimensional. A traverse system was used to move the probes to a range of locations. To ensure similarity between the measurements, the seven-hole probe was moved eight times more often to account for the difference in measurement capability.

At each location, the flow was sampled for 8 seconds. To ensure that the movement of the probe did not interfere with the measurements, the first and final 1.5 seconds of each sample were discarded, resulting in an actual sample time of 5 seconds. The pressure scanner measures the pressure at a rate of 100 Hz, resulting in a sample size of 500 points for each location. This was deemed sufficient for the scope of this test.

Fig. 3: A seven-hole probe characterising the flow field downstream of a vane cascade.

IV. INITIAL GEOMETRY ISSUES

Upon conducting initial tests, it was immediately clear that the date from the pitot rake was incredibly noisy. After some further testing, the source of the error was traced back to the jagged geometry of the pitot tube inlets.

As a result, the rake was disassembled and each pitot tube was carefully sanded under a microscope. As shown in Fig. 4, this process resulted in a substantially smoother profile and noise in the data was reduced to satisfactory levels.

Fig. 4: Microscopy photograph of the pitot tube before (left) and after (right) it was carefully sanded.

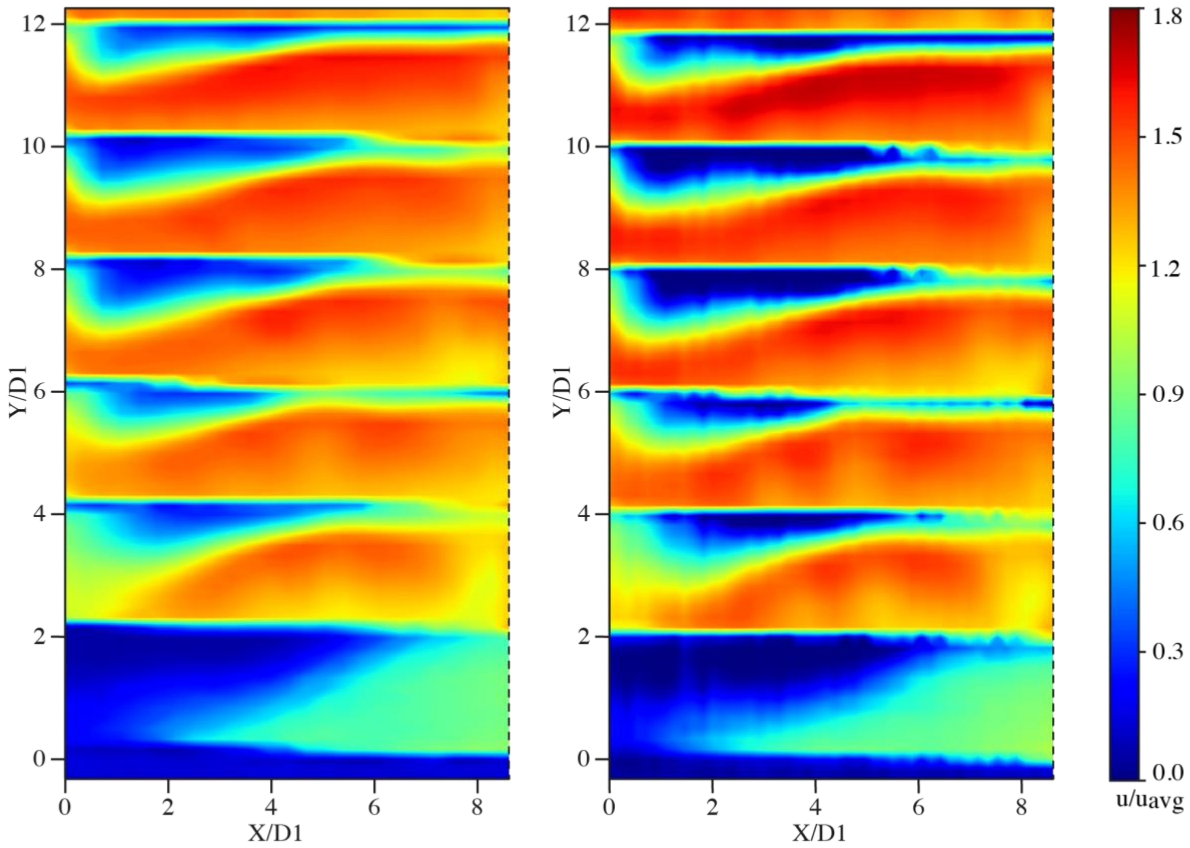

Fig. 5: Velocity contour downstream of the turning vanes, measured by the seven-hole probe (left) and the pitot rake (right). The u_{avg} was 21.97 and 18.36 respectively. D_1 is the inlet spacing of the vanes at 18mm.

V. RESULTS AND DISCUSSION

The flow field downstream of the vanes was assessed through a measurement grid of 24 points horizontally and 77 points vertically. In total, the velocity was sampled at 1848 points. The pitot rake completed all measurements within 67 minutes, while the seven-hole probe required 539 minutes for the same task. This equates to a speed-up by a factor of 8, which is in line with predictions.

The test measured the first six vane channels from the side of the channel to the centre, shown as a dashed line in Fig. 5. It is evident that the measured velocity contours are similar, although the seven-hole probe produces smoother results. There are several reasons for this. When sampling with the seven-hole probe, each location is sampled with the same probe geometry. This means that measurements and errors are consistent.

With the pitot rake, the locations are sampled by eight different pitot tube geometries. While one tube might give an excessively high pressure, its neighbour might produce a measurement that is consistently too low. Ultimately, this leads to the streaks seen in the right contour.

Furthermore, the seven-hole probe is less sensitive to misalignment with the flow than the pitot rake. For instance, at an angle of attack of merely 14°, the measurement error can be expected to be at least 6% [7].

Additionally, the machining tolerances on the seven-hole probe are smaller and the overall build quality is higher. This results in fewer measurement errors. Of course, this is to be expected from a device that has a base price of €1080 with an additional calibration cost of €1350 (total €2430), while the pitot rake cost less than €50 to manufacture.

While the flow fields are similar, the average measured velocity measured by the pitot rake is approximately 16% lower than the measurements taken with the multi-hole probe. This suggests that there is a systematic issue with the probe tip geometry. Due to sub-millimetre scales, its manufacture is certainly the most difficult out of any component of the pitot rake.

These tests do not take into account the additional complexity involved in processing the data from the seven-hole probe. While the connections and setup of the pitot rake and seven-hole probe are similar, data processing is not. The pressures from the rake can be converted to velocities through the use of a single equation. The pitot rake, on the other hand, requires the use of computationally intensive look-up tables and calibration files [8].

VI. Conclusion

It has been shown, that it is possible to manufacture a low-cost pitot rake to measure the flow in wind tunnels. The strengths of pitot rakes and multi-hole probes are summarised as follows:

- Pitot rakes can be manufactured at a fraction (5%) of the price of standard seven-hole probes
- Pitot rakes are capable of collecting data significantly faster.
- The data collected from pitot rakes are processed much more easily
- Seven-hole probes are more tolerant to varying angles of incoming flow
- Seven-hole probes can measure all components of velocity
- The purchased seven-hole probe was of higher manufacturing quality, thereby reducing measurement errors

In conclusion, the pitot rake presented here is a viable alternative if an approximate measurement of the flow is required. Its faster sample rate means that the flow field can be scanned in minutes, rather than hours. However, if the incoming flow is at a larger angle or if more accurate measurements are required, the seven-hole probe is still the better option, assuming that it is within budget.

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