AERODYNAMIC PROBE MEASUREMENTS WITH SPARSE CALIBRATIONS

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ABSTRACT

Current multi-hole pneumatic probes require bespoke, time-consuming calibrations. Two topics are addressed in this paper: the repeatability of 3D-printed 5-hole probe calibrations, and the sparse calibration of systematically deformed 5-hole probes.

First, ten 3D-printed 5-hole probes of diameter 3.5mm are calibrated and compared. Averaged differences between probe calibrations are 0.3° in flow angle, 0.24% dynamic head in stagnation pressure and 0.90% dynamic head in static pressure. These are comparable to the repeatability of the calibration facility, determined by calibrating one probe multiple times. This demonstrates that 3D printing can produce geometric consistency such that bespoke probe calibrations are not necessary.

Second, 5-hole probes are 3D-printed with geometric defects commonly found in conventionally manufactured steel probes. A Principle Component Analysis (PCA) approach is used to produce a series of calibration map mode shapes. From these, optimal sparse measurement locations are identified which reduce the number of calibration measurements required by 93%. This sparse calibration method reduces measurement errors for a 3D-printed deformed probe by 56% and a conventional steel probe by 61%, compared to using a reference calibration map.

INTRODUCTION

Conventional multi-hole probes are manufactured by soldering together a bundle of steel hypodermic tubes and machining the head to the required shape. This process is prone to errors in the probe head geometry, meaning a bespoke calibration is required. For 5-hole probes, the calibration takes around 1 hour. However, more complex probes, such as a 9-hole probe that resolves the gradient and curvature of the pressure field, can require 1000s of hours to calibrate, thus motivating the need for sparse calibration techniques.

A study by Hall and Povey [1] showed that additive manufacturing improves the consistency of 5-hole probe geometries with head diameters of 4mm to 12mm. In this paper, the consistency of 3D-printed 5-hole probes with 3.5mm diameter heads is investigated, as well as introducing a method to account for geometric errors in manufacturing without requiring a full, bespoke calibration for each probe.

RESULTS AND DISCUSSION

A series of 10 probes of 3.5mm diameter and the same nominal geometry are 3D-printed. Each probe is calibrated over a range of ±30° in yaw and ±20° in pitch. The average of the ten calibration maps is used as a reference calibration map. For each probe the error between the true calibration of the probe and the reference calibration are calculated, resulting in an average error of 0.3° in yaw and pitch angle, and 0.24% and 0.90% of dynamic head error in stagnation and static pressure, respectively. The error in a true calibration map, evaluated by calibrating the same probe multiple times, is found to be around 60% of these errors. This indicates, for nominally identical probes, an existing, reference calibration map can be used instead of a new bespoke calibration.

To account for geometric defects in the probe head, the image reconstruction from sparse data method of Manohar *et al*. [2] is used. To generate a database of different calibration maps, 14 additional 5-hole probes with deliberately designed geometric errors are printed and calibrated. Manohar *et al*.'s method [2] uses Principle Component Analysis (PCA) to identify a small number of significant mode shapes, shown for the stagnation pressure calibration coefficient in Fig. 1(a). A set of optimal measurement locations, shown in Fig. 1(b), are found using 8 mode shapes for each probe calibration coefficient. These sparse calibrations require only 6.7% of the measurements of a full calibration.

Three probes with multiple geometric errors are 3D-printed, tested then processed using both the reference calibration map of the nominal geometry probes, and a sparse calibration. This results in the average stagnation pressure errors shown in Fig. 1(c). The sparse calibration reduces the error by 56% on average, with similar magnitudes of reductions for flow angle, and static pressure measurements. A 1.3mm diameter steel probe, manufactured to a similar design as the nominal probe geometry, is also tested using these methods. Using the sparse calibration technique reduces the measurement error by 61%. The absolute error for the steel probe using the sparse calibration is around three times larger than the 3D-printed probes, as the database does not include some geometric differences between the steel and 3D-printed probes.

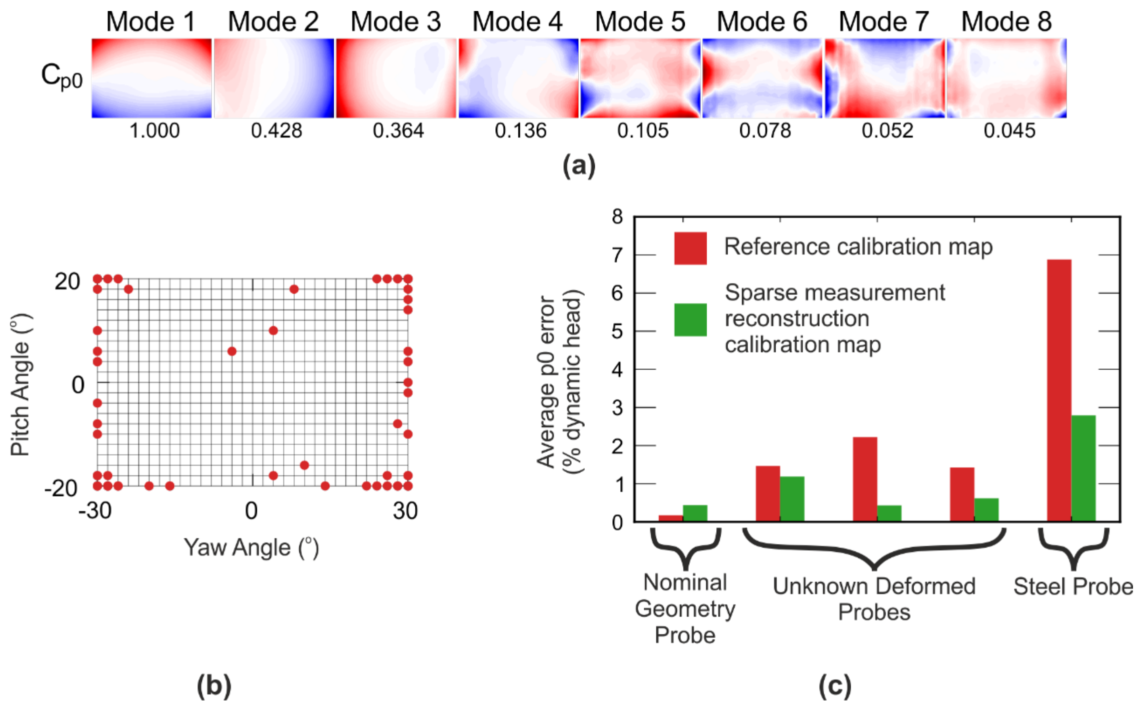

Figure 1. Results of sparse calibration method for stagnation pressure. (a) Contours of stagnation pressure coefficient modes calculated using PCA and the corresponding singular values. (b) Sparse measurement locations for calibration. (c) Comparison of average errors in stagnation pressure using reference calibration map and sparse measurement technique for different probes.

REFERENCES

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