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An Experimental Study of Calibration Algorithms for Five-Hole Pressure Probes

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Abstract

This study aims to investigate various calibration algorithms for five-hole pressure probes and their uncertainty in 3-D velocity measurement of aerodynamic flows. The experimental study is conducted in a low speed open-circuit wind tunnel. A conical five-hole pressure probe of 90°-conical angle is built and used for the experiment. The calibration of the probe covers flow directions in the range of ±30° pitch angles and ±30° yaw angles. Three different calibration models are developed and investigated for the quality of flow velocity measurement. These are a conventional calibration algorithm for five-hole probe, a modified calibration algorithm, and a generalized calibration algorithm for multi-hole probe, In the testing, flows of variety directions are examined. The results are presented as the comparisons of calibration curves and uncertainties of velocity components. The quality of measurement in low angular flow and high angular flow are also analyzed and discussed.

***Keywords**:* pressure probe, flow measurement, velocity measurement, aerodynamic flows, calibration algorithm

1. Introduction

Five-hole pressure probe is extensively used in aerodynamic tests for many years. It is used to measure three-dimensional velocity of fluid flows by detecting static pressures at five different pressure tubes located on the probe head and then being interpreted into three components of velocity or direction of the flows. The process of velocity interpreting is done using a calibration algorithm. The accuracy of the velocity measurement depends on variety of factors. Calibration algorithm of the probe is one of those factors and is very important.

1.1 Calibration Techniques

In calibration of a five-hole pressure probe, the relations between the pressures on each pressure tube and the velocity vectors of the flow will be formed. This involves with non-linear formulation and can be done with various mathematical models or algorithms.

In 1979 Treaster and Yocum [1] successfully developed a calibration technique of five-hole pressure probe and this technique has been conventionally used until today. In their works, 4 different non-dimensional pressure coefficients had been created from the pressures at the five holes and formulated for a relationship of each component of the flow direction to two selected pressure coefficients. In 1994, Bruce and Bruce [2] modified the conventional algorithm by relating the pressure coefficients to the velocity components (vertical and lateral velocity) instead of the direction components (pitch and yaw angles). In 2012, Tolga and Guillamo [4] defined different formula of pressure coefficients and presented relations of each component of flow directions to all 4 pressure coefficients. Their technique can be applicable to multi-hole pressure probes and even to the probes of unsymmetrical-hole position.

1.2 Objectives

The purpose of this work is to study these three different calibration algorithms to a five-hole pressure probe in velocity measurement of air flows. The study will be conducted based on experiment using a low speed wind tunnel. The calibration results and uncertainty of various directions of velocity measurement will be investigated and compared.

1.3 Nomenclature

CP	Calibration pressure coefficient
v	Lateral velocity component
w	Vertical velocity component
α	Pitch angle
β	Yaw angle

Subscripts

c	Calibration Algorithm
r	Actual
s	Static properties
T	Total properties

2. Experimental Device and Setup

2.1 Five-hole Pressure Probe

Five-hole pressure probe used in this work is a conical head type of 90°-conical angle. One hole is located at the center of the head and 4 holes are positioned symmetrically on the side of the cone head as shown in Fig.1. Each hole is drilled so that they are perpendicular to the surface and causing circular shapes on the surface and having diameter of 0.5 mm.

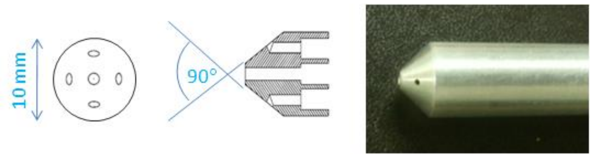


Fig. 1 Geometry of conical five-hole pressure probe

2.2 Experimental Setup

Experiments are carried out in an open-circuit wind tunnel having test section of 1ft. x 1ft. and contraction ratio of 9:1. All measurements are performed under free-stream velocity of 20 m/s which is monitored using a pitot-static probe located at the same station of the five-hole pressure probe.

The five-hole pressure probe is mounted so that the probe tip is positioned stationary at the middle of the test section. The pitch angle and the yaw angle of the probe can be controlled manually outside the test section with the precision of ±0.5°. In this study, the probe is calibrated over an angular range of ±30° pitch angle (-30°≤ α ≤ 30°) and ±30° yaw angle (-30° ≤ β ≤ 30°).

In calibration of the probe, velocity components may be needed to be defined according to the pitch angle and the yaw angle as the following equations.

$$w = U_\infty \sin\alpha \tag{1}$$

$$v = U_\infty \cos\alpha \cdot \sin\beta \tag{2}$$

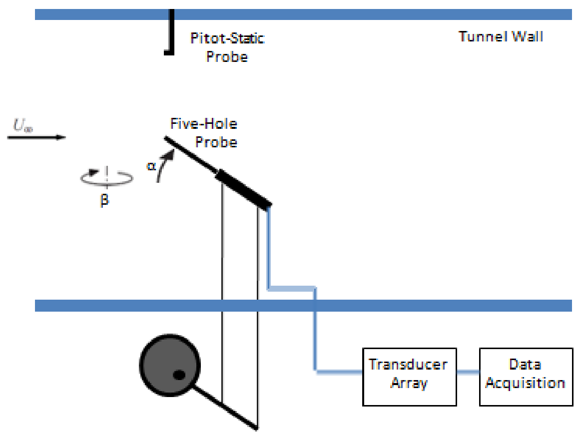


Fig. 2 Schematic of experimental setup

The five-hole pressure probe is connected to five differential pressure transducers (phidget 1136) with a silicone tube of 2 m length. The pressure transducers have their range of 2 kPa with ±6% accuracy. The signal from the transducers is then transformed to digital signals and acquisitioned into a PC memory via the data acquisition system as shown schematically in Fig. 2

3. Calibration Algorithms

Fig. 3 shows the hole-numbering of the probe used in calibration. The pressure at each hole will be numbered corresponding to their hole numbering as P_1, P_2, P_3, P_4, and P_5, and so as the pressure coefficients.

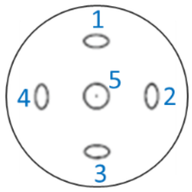


Fig. 3 Hole numbering of pressure probe

3.1 Conventional Calibration Algorithm

The calibration technique which is conventionally used is presented by Treaster and Yocum [1], In this technique, the pitch angle and yaw angle and velocity magnitude of flows are calculated using 4 non-dimensional pressure coefficients defined as Eqs. 3-6 below.

$$CP_\alpha = \frac{P_3 - P_1}{P_5 - P_{ave}} \tag{3}$$

$$CP_\beta = \frac{P_2 - P_4}{P_5 - P_{ave}} \tag{4}$$

$$CP_{ave} = \frac{P_{ave} - P_s}{P_T - P_s} \tag{5}$$

$$CP_T = \frac{P_5 - P_s}{P_T - P_s} \tag{6}$$

Each pitch and yaw angle are associated to a unique CP_α and CP_β, whereas the velocity magnitude is associated to a unique CP_{ave} and CP_T. The relationship among these parameters are traditionally presented using calibration curves provided at several flow speeds and directions. An example of calibration curves of a conical five-hole probe is shown in Fig. 4.

The calibration curves can be used either to interpolate for the results or to generate a general formula. Bruce and Bruce [2] recommended the formula is generated as Taylor series as follow.

$$\alpha = \sum_i^n \sum_j^n c_{i,j} CP_\alpha{}^i \cdot CP_\beta{}^j \tag{7}$$

$$\beta = \sum_i^n \sum_j^n d_{i,j} CP_\alpha{}^i \cdot CP_\beta{}^j \tag{8}$$

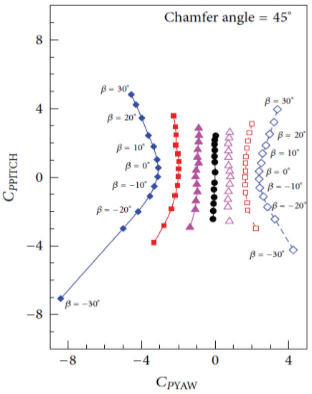


Fig. 4 Calibration curve of five-hole probe [5]

3.2 Modified Calibration Algorithm

Modified calibration algorithm presented by Bruce and Bruce [2] is an algorithm to form the relations between the pressure coefficients and the velocity components instead of pitch and yaw angles of the flow. The flow direction needs to be converted into the velocity components using Eqs. 1 and 2 to build calibration curves. When applying the probe for a measurement, the five pressures detected from the probe can then be used to determine the velocity components using Taylor series approximation as following formulations.

$$w = \sum_{i}^{n}\sum_{j}^{n} a_{i,j} CP_{\alpha}{}^{i} \cdot CP_{\beta}{}^{j} \qquad (9)$$

$$v = \sum_{i}^{n}\sum_{j}^{n} b_{i,j} CP_{\alpha}{}^{i} \cdot CP_{\beta}{}^{j} \qquad (10)$$

3.3 General Algorithm for Multi-Hole Probe

Tolga and Guillermo [4] provide general algorithm used for multi-hole pressure probes in which the calibration pressure coefficients are defined with different formula. For five-hole probe, the 4 pressure coefficients are defined as follows.

$$CP_1 = \frac{P_1 - P_s}{P_5 - P_s} \qquad (11)$$

$$CP_2 = \frac{P_2 - P_s}{P_5 - P_s} \qquad (12)$$

$$CP_3 = \frac{P_3 - P_s}{P_5 - P_s} \qquad (13)$$

$$CP_4 = \frac{P_4 - P_s}{P_5 - P_s} \qquad (14)$$

All these 4 pressure coefficients are used to calculate for the pitch and yaw angles as Eqs. 15 and 16. This can be done using either interpolation technique or Taylor series approximation.

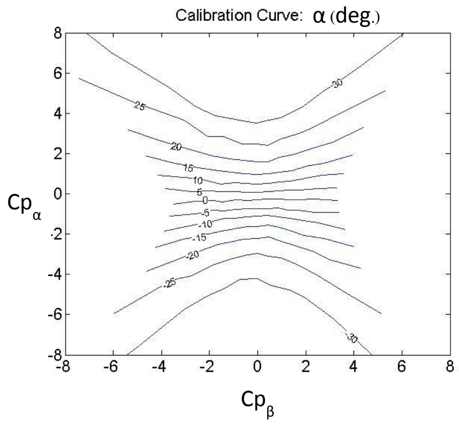
$$\alpha = f(CP_1, CP_2, CP_3, CP_4) \qquad (15)$$

$$\beta = f(CP_1, CP_2, CP_3, CP_4) \qquad (16)$$

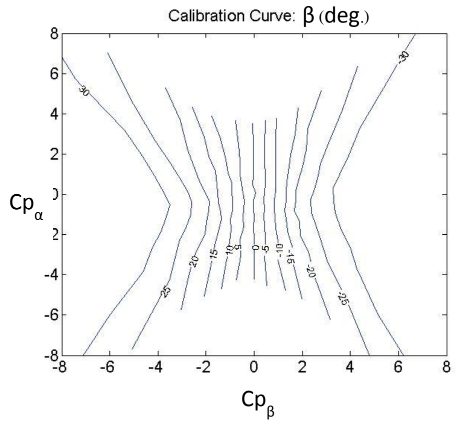
4. Results and Discussion

4.1 Calibration Results

All 3 calibration methods were examined through the range of ±30° pitch angle and ±30° yaw angle and at 5° increment step, causing the measurement of total 169 points be performed for each calibration. These set of data were then rearranged in order to be plotted in a typical calibration curve forms. The results are presented in Figs. 5-7.



(a)



(b)

Fig. 5 Calibration curves of conventional algorithm

The calibration curves of the conventional algorithm presented in Figs. 5a and 5b shows the contours of pitch angle and yaw angle against CP_α and CP_β, respectively. The contour curves are in well-organized form and almost symmetry meaning that the interpolation or mathematical models could be achieved. In addition, this verifies the design, fabrication of the probe, experimental set up, and calibration procedures. It is also shown that CP_α changes majorly with the pitch angle (α) but merely little with the yaw angle (β). While CP_β changes majorly with the yaw angle but only little with the pitch angle. This is reasonable and also compared well to those of Nekkanti S. and Kancerla [5]. However, this will also be confirmed in the uncertainty analysis in the next section.

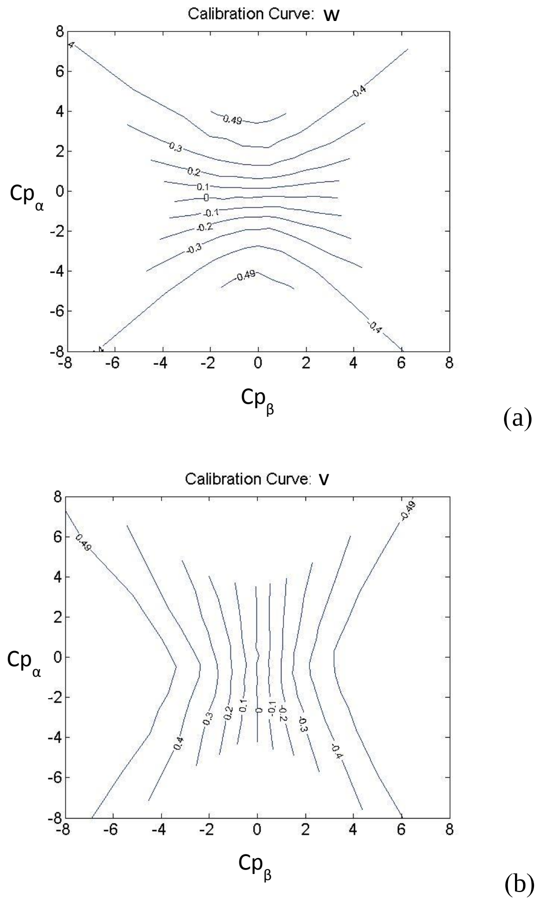


Fig. 6 Calibration curves of modified algorithm

Fig. 6 shows the contours of vertical and lateral velocity components (v, w) using the modified algorithm. The shapes of the contours are similar to those of the contours in Fig. 5. This is reasonable as the vertical and lateral velocity components are functions of the pitch and yaw angles, respectively.

The calibration curves of the general algorithm for multi-hole pressure probe are presented in Fig. 7. This shows the contours of CP_1, CP_2, CP_3, and CP_4 against the pitch and yaw angle. These show CP_1 and CP_3 change majorly with the pitch angle, while CP_2 and CP_4 change majorly with the yaw angle.

The results from all 3 calibration methods show the calibration curves are in well-organized form and should be able to form functions between the pressure coefficients and the pitch and yaw angles. In this study, the Taylor series approximation is applied to all calibration algorithms and the results are presented in the next section.

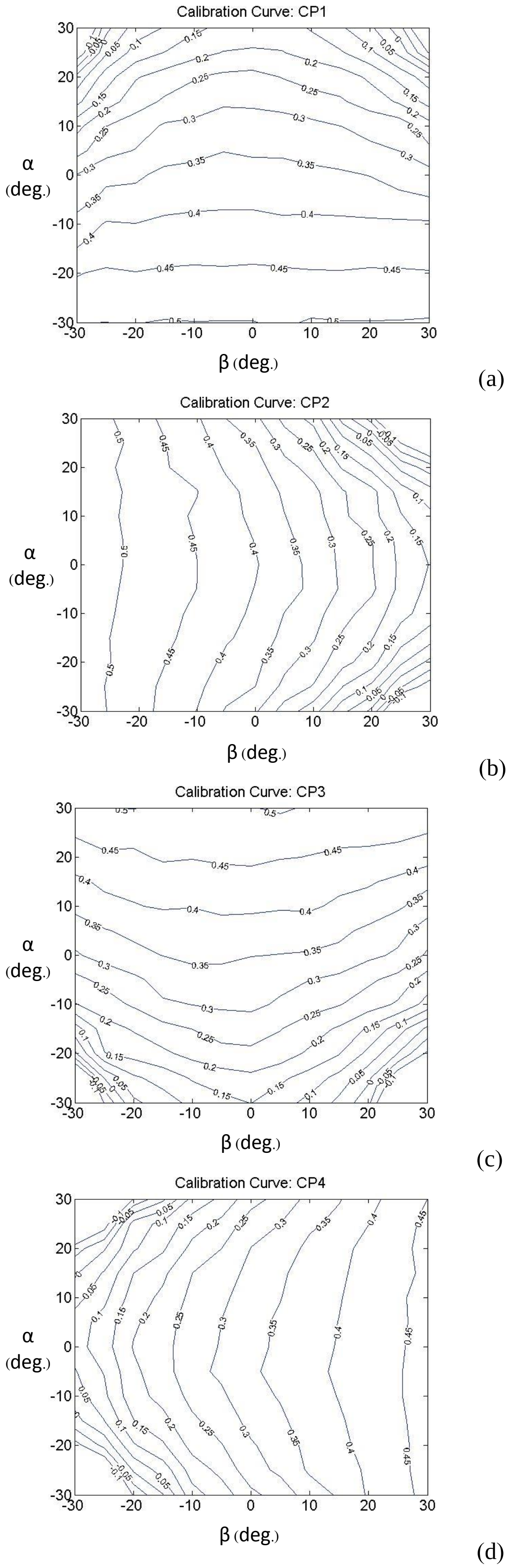


Fig. 7 Calibration curves of algorithm general for multi-hole probe

4.2 Uncertainty Results

All the calibration curves generated in previous section were used to formulate the relationship between the flow direction or velocity components and the pressure coefficients. The Taylor series of 5th order were applied to all three calibration algorithms in order to determine the flow direction and velocity components from the measured pressures of the five holes. To be able to compare, we need to convert all results into velocity components (v and w). For the 5th order approximation, Eqs. 7 and 8 can be expanded as Eqs. 17 and 18 respectively, and the coefficients can be solved using regression analysis.

$$\begin{aligned}\alpha = {} & c_{00}+c_{10}CP_\alpha+c_{01}CP_\beta \\ & +c_{20}CP_\alpha{}^2+c_{11}CP_\alpha CP_\beta+c_{02}CP_\beta{}^2 \\ & +c_{30}CP_\alpha{}^3+c_{21}CP_\alpha{}^2CP_\beta+c_{12}CP_\alpha CP_\beta{}^2+c_{03}CP_\beta{}^3 \\ & +c_{40}CP_\alpha{}^4+c_{31}CP_\alpha{}^3CP_\beta+c_{22}CP_\alpha{}^2CP_\beta{}^2+c_{13}CP_\alpha CP_\beta{}^3 \\ & +c_{04}CP_\beta{}^4+c_{50}CP_\alpha{}^5+c_{41}CP_\alpha{}^4CP_\beta+c_{32}CP_\alpha{}^3CP_\beta{}^2 \\ & +c_{23}CP_\alpha{}^2CP_\beta{}^3+c_{14}CP_\alpha CP_\beta{}^4+c_{05}CP_\beta{}^5\end{aligned} \tag{17}$$

$$\begin{aligned}\beta = {} & d_{00}+d_{10}CP_\alpha+d_{01}CP_\beta \\ & +d_{20}CP_\alpha{}^2+d_{11}CP_\alpha CP_\beta+d_{02}CP_\beta{}^2 \\ & +d_{30}CP_\alpha{}^3+d_{21}CP_\alpha{}^2CP_\beta+d_{12}CP_\alpha CP_\beta{}^2+d_{03}CP_\beta{}^3 \\ & +d_{40}CP_\alpha{}^4+d_{31}CP_\alpha{}^3CP_\beta+d_{22}CP_\alpha{}^2CP_\beta{}^2+d_{13}CP_\alpha CP_\beta{}^3 \\ & +d_{04}CP_\beta{}^4+d_{50}CP_\alpha{}^5+d_{41}CP_\alpha{}^4CP_\beta+d_{32}CP_\alpha{}^3CP_\beta{}^2 \\ & +d_{23}CP_\alpha{}^2CP_\beta{}^3+d_{14}CP_\alpha CP_\beta{}^4+d_{05}CP_\beta{}^5\end{aligned} \tag{18}$$

Uncertainty of the measurement was analyzed for each point throughout calibration range (±30° pitch angle and ±30° yaw angle) and in the form of % error relative to the freestream velocity as follow.

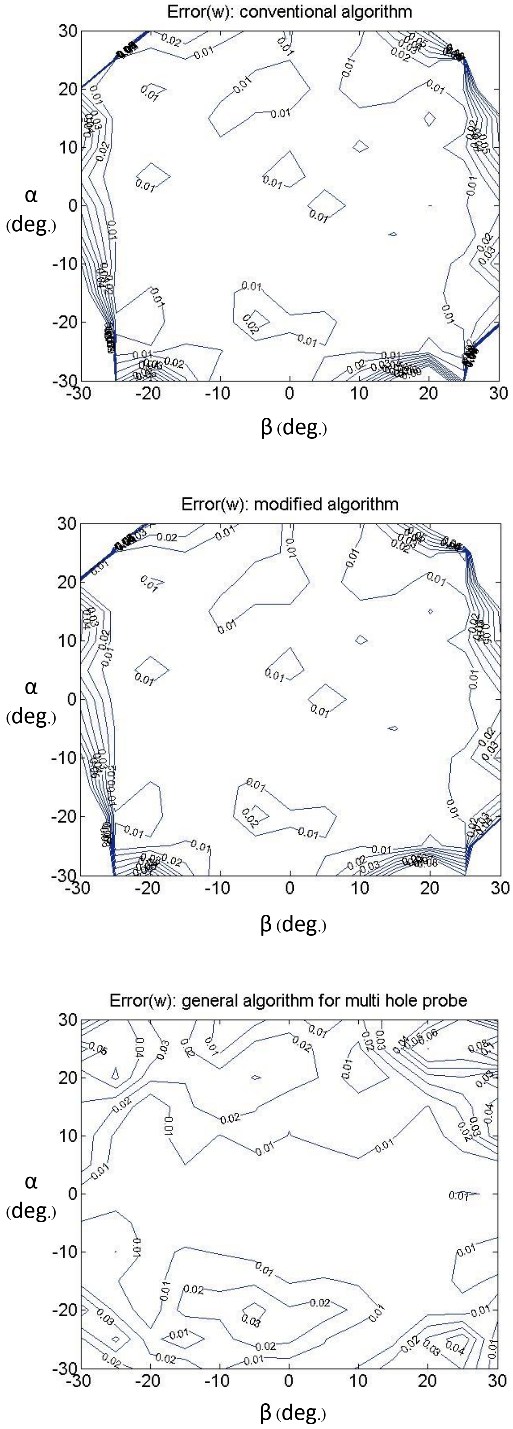
$$Error(v)=\frac{|v_c-v_r|}{U_\infty} \tag{19}$$

$$Error(w)=\frac{|w_c-w_r|}{U_\infty} \tag{20}$$

where v_c and w_c are the measured velocity components using the studied algorithms; v_r and w_r are the actual velocity components; and U_∞ is the freestream velocity.

The errors of vertical and lateral velocity measurement using the five-hole pressure probe are presented as contour plots against the pitch and yaw angles as shown in Figs. 8 and 9, respectively.

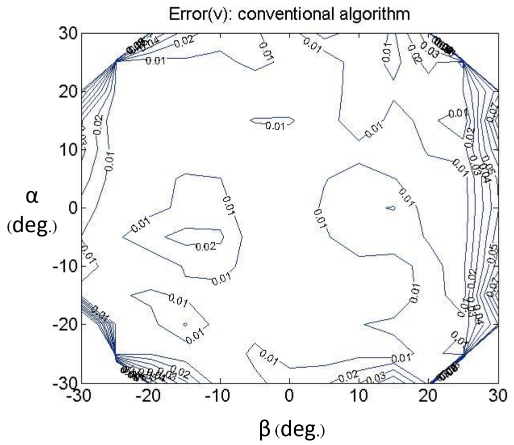
Figs. 8a, 8b, 9a, and 9b show that the errors of the measurement of the vertical and lateral velocity components using the conventional algorithm and modified algorithm are similar. The measurement within ±25° pitch and yaw angles provide within 2% error, however near the boundary of calibration range the error increase to 10% causing average error of 3.4%.



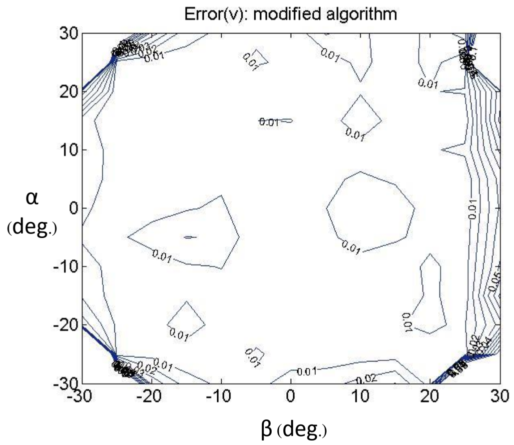
(a) (b) (c)

Fig. 8 Errors of vertical velocity measurement using (a) conventional algorithm (b) modified algorithm (c) general algorithm for multi-hole probe

Figs 8c and 9c show that the errors of the measurement within ±25° pitch and yaw angles using the general algorithm for multi-hole probe are quite in the same range as the other 2 algorithms as within 2% error. However, the measurement near the boundary of calibration range show better results as the error increase a little to about 5% causing average error of 2.7%. This could be explained that because in general algorithm, there are more terms of Taylor series in the calculation for the solutions, in fact, it is about double. There are 21 polynomial terms in conventional and modified algorithms, while 41 polynomial terms in the general algorithm for multi-hole probe. Another reason of the better results using the general algorithm is that the flow pitch and yaw angle are formulated in relation to all 4 pressure coefficients, while the other 2 algorithms are formed in relation to only 2 pressure coefficients.



(a)



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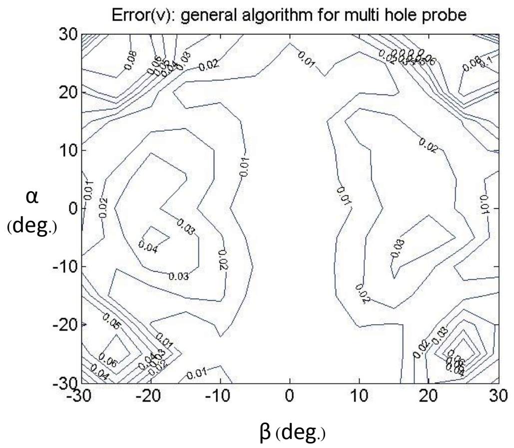

(c)

Fig. 9 Errors of lateral velocity measurement using (a) conventional algorithm (b) modified algorithm (c) general algorithm for multi-hole probe.

5. Conclusion

The present works in experimental investigation of calibration algorithm to its uncertainty of measurement using a conical five-hole pressure probe can be concluded as follows.

(1) The conventional calibration algorithm and the modified calibration algorithm provide the same quality of measurement, within 2% error within the range of ±25° pitch and yaw angle

(2) The general calibration algorithm for multi-hole pressure probe provide more accuracy in overall range of measurement, especially at very high pitch and yaw angles

6. Acknowledgement

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