Calibration of a Five-Hole Multi-Function Probe for Helicopter Air Data Sensors

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Abstract

In the flight of air vehicles, accurate air data information is required to control them effectively. Especially, helicopters are often put in drastic motion involved with high angle of attacks in order to perform difficult missions. Among various sensors, the multi function probe (MFP) has been used in the present study mainly owing to its advantages in structural simplicity and capability of providing various information such as static and total pressure, speed, and pitch and yaw angles. In this study, a five-hole multi-function probe (FHMFP) is developed and its calibration is conducted using multiple regressions. In this work a calibration study on the FHMFP, an air data sensor for helicopters, is reported. It is shown that the pitch and yaw angles' accuracy of calibration is ±0.91° at a cone angle of 0° ~ 30° and ±2.0° at 30° ~ 43°, respectively, which is summarized in table 3.

Key words : five-hole multi-function probe(FHMFP), air data sensor, calibration, multiple regressions

Introduction

Air vehicles which are flying, accurate air data information is required to navigate in the air safely and to control them effectively. Especially, helicopters are often put in drastic motion involved with high angle of attacks in order to perform difficult missions. It is, therefore, necessary to design an effective sensor to obtain accurate air data. Among various sensors, pitot-tube, GPS, and mobile vane, the multi function probe (MFP) has been used in the present study mainly owing to its advantages in structural simplicity and capability of providing various information such as static and total pressure, speed, and pitch and yaw angles. So MFP can be useful for study on the 3-d fluid flow as well as air data sensor of air vehicles.

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The existing studies on the MFP are mostly calibration methods. The parameters which may affect on the accuracy of measurements are Reynolds number, Mach number, turbulent elements, gradient of velocity, and wall proximity. In case of the geometry of 5−hloe probe, shape of the nose part, the direction of the pressure hole and cone angle also affects the measurements.

To measure 3−dimensional flow field using 5−hole probe, it is necessary for 5−hole probe to calibrate. Calibration method can be significantly divided into two kinds; Nulling method and non−nulling method. Nulling method is to move the probe axis angle being consistent with the direction of flow; the pressure of four−hole become the same except for the center hole. After determine the direction of flow, the velocity is obtained by measured pressure at that time. The turning angle can be measured more accurately than the non−nulling method, but this nulling method needs more space for traversing system and long data acquisition time since the probe must be pitched and yawed at each measurement location until the four pressures are equal. In the non−nulling method the probe is fixed and the pressure of each hole is measured. The angle of attack and side slip angle are calculated by coefficients obtained using five pressure data. The non−nulling method has been more useful because it does not need much space and time.

Recognizing the need to study a multi−function velocity direction sensor that enables simultaneous measurement of velocity, angle of attack, and angle of sideslip so as to improve the performance of air data systems for helicopters, as opposed to the existing method that measures velocity only, the present study aimed at designing a five−hole multi−function probe by using a CFD analysis and optimization techniques, and subsequently created FHMFP based on configuration design results. Wind tunnel tests were then carried out to apply the calibration method in multiple regressions to validate the performance of the five−hole multi−function probe.

Design of FHMFP

2.1 Basic theory of five-hole probe

Fig. 1 shows schematic of a five−hole probe. The probe calibration procedure for the non−nulling method is to place the probe in a known flow and vary the pitch and yaw of the probe over a matrix of angles which exceed the flow angles expected in the flow field to be measured. At each location in the matrix, the five hole probe measure the direction as well as magnitude of the flow using pressure[1]. In case of the non−nulling method, total pressure, static pressure, the angle of attack and side slip angle are calculated by measured pressure: P1, P2, P3, P4, P5. Each pressure is a function of velocity, AOA and AOS. There are four coefficients which are used to calibrate, as follows;

$$Cp_{pitch} = (P_5 - P_4)/(P_1 - \overline{P}), \tag{1}$$

$$Cp_{yaw} = (P_3 - P_2)/(P_1 - \overline{P}), \tag{2}$$

$$Cp_{total} = (P_5 - P_T)/(P_5 - \overline{P}), \tag{3}$$

$$Cp_{static} = (\overline{P} - P_S)/(P_1 - \overline{P}), \tag{4}$$

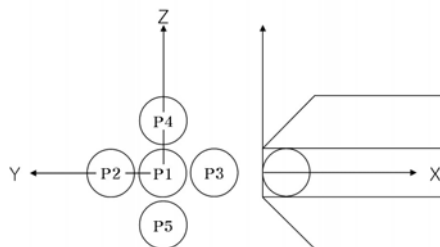$$\overline{P} = (P_2 + P_3 + P_4 + P_5)/4. \tag{5}$$

Fig. 1. Schematic of a five−hole probe

2.2 CFD analysis

Fig. 2 shows the grid configurations of models on which computational fluid dynamics studies were performed in this study. A space surrounding the probe was created and the analytical model was subjected to an external flow field, and unstructured grids were formed where the model came in contact with the probe nose. Structured grids were used in the external flow field and the interior of the probe. A far field boundary condition was set for the external flow field, and the model was made 10 times larger than the probe, as the effect of viscosity should not reach the probe's tip[2]. In this study, Fluent V6 based on the compressible Navier-Strokes governing equation was used for the numerical analysis of the five-hole probe[3].
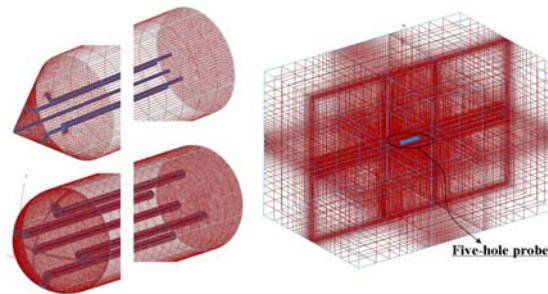

Fig. 2. Grid configurations for CFD analysis

2.3 Optimization technique

Two configurations a cone configuration and a hemispherical configuration – were optimized for this study. As for the pressure hole direction, a vertical probe displayed superior calibration performance to that of a horizontal probe, and there was little change in the calibration curve against the Reynolds number[4]. The overall diameter and length of the two configurations based on the vertical probe were fixed at 30 mm and 200 mm. Based on these initial conditions, a response surface method was applied to perform optimization. The response surface method offers advantages of expressing numerical analysis noise data in a smooth, moderate manner and enabling fast convergence results. Nine test points were

$$O.F = Max.(\Delta P),$$
$$\Delta P = (P_5 - P_4), \quad P = f(X_1, X_2). \tag{6}$$

selected by 3^n for two variables by using a full factorial design. In addition, as shown in Fig. 3, the cone angle and the hole diameter were set as the design variables for the cone configuration and the hole angle from the center of the hemisphere and the hole diameter were set as the design variables for the hemispherical configuration. Equation (6) shows the objective function of this study whose objective value is to maximize the pressure difference between each pressure hole depending on the change in the angle of attack within the helicopter's operational angle of attack of 25°.
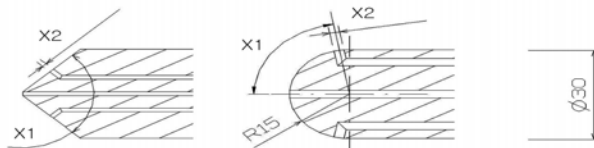

Fig. 3. Design variables for optimization

Analysis Result of FHMFP

3.1 Result of design

   In this study, a CFD analysis was performed at the maximum angle of attack of the helicopter at 25°, and Tables 1 and 2 suggest differences in pressure obtained from analyses at 9 test points with the cone configuration and hemispherical configuration, respectively. Fig. 4 and Fig. 5 illustrate response surfaces based on the results of CFD analysis of each configuration. As for the cone configuration, the optimal cone angle variable based on the hole's diameter is 70°, while the hole diameter is 1 mm. As for the hemispherical configuration, the initial optimum configuration is 48° for the hole angle and 0.5 mm for the hole diameter. But the hole's minimum diameter was limited to 1mm. Because if the hole diameter is too small in actual flight environment, it could hamper measurement of pressure due to foreign bodies and the moisture between the holes. And the almost of five-hole probe and pitot-tube as air data sensors, the products of Goodrich and Aerosonic, are bigger than 1 mm for the hole diameter, such as 2, 3, 6 and 7 mm. Due to the limitation in the size of the hole diameter in the flight environment, the optimum configuration was found to be 48° for the hole angle and 1 mm for the hole diameter.

Table 1. Design of Experiments and Result(Cone)

Experimental Point	X_1	X_2	Δp
1	55	1.5	4931
2	125	1	3773
3	55	1	5018
4	90	1	4915
5	55	0.5	5034
6	125	0.5	3556
7	125	1.5	3661
8	90	0.5	4850
9	90	1.5	4954

Table 2. Design of Experiments and Result(Hemisphere)

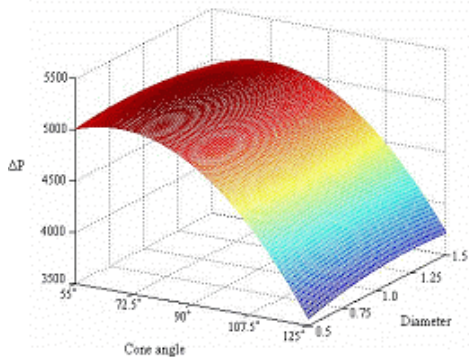| Experimental Point	X_1	X_2	Δp
1	45	1.5	8758.4
2	55	1	8657.4
3	45	1	8742.9
4	50	1	8820.0
5	45	0.5	8909.2
6	55	0.5	8718.8
7	55	1.5	8652.5
8	50	0.5	8921.2
9	50	1.5	8847.4

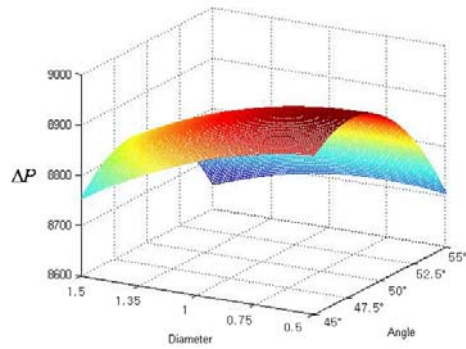Fig. 4. Response Surface of Pressure
Difference (Cone)

Fig. 5. Response Surface of Pressure
Difference (Hemisphere)

3.2 Comparison of calibration performance

In general, the five-hole probe, whose calibration accuracy is relatively superior, maintains even intervals of the point distribution overall while showing large points [4]. Calibration curve distribution charts (Fig. 6 and 7) suggest that the cone configuration would lead to a relatively large standard error when calibrating within a 25° of angle of attack, which is the operational range of a helicopter, as it has wide intervals between points that are unevenly distributed when the angle exceeded 15°. As for the hemispherical configuration, the intervals are narrow but are evenly distributed overall, implying that more accurate values can be expected when the overall size is enlarged and calibration is performed, making it suitable for installation on a helicopter.
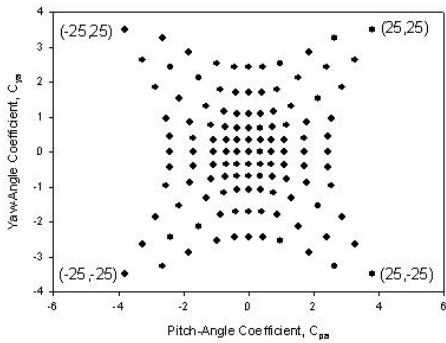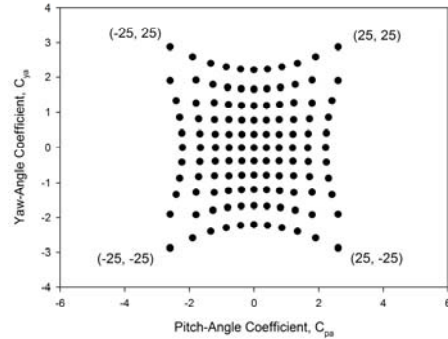

Fig. 6. Cp_{pitch} and Cp_{yaw} of optimized Cone

Fig. 7. Cp_{pitch} and Cp_{yaw} of optimized Hemisphere

Wind Tunnel Test for Calibration

4.1 Equipment for wind tunnel test

The wind tunnel used for the calibration test is a circular, open-type wind tunnel with a diameter of 300 mm where measurements are performed, and the flow speed can be varied from 0 m/s to 50 m/s. The turbulence intensity is less than 0.6% in all velocity ranges.
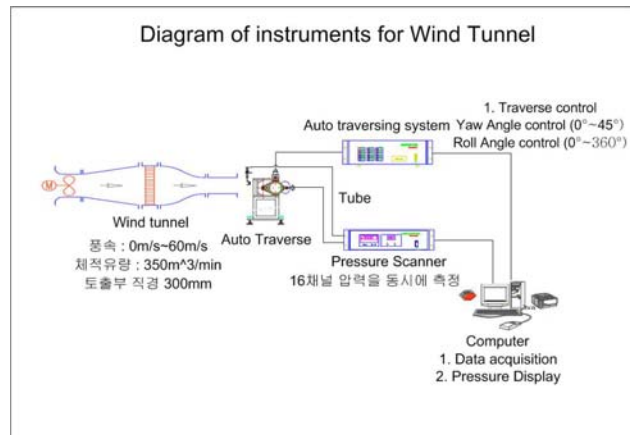
Fig. 8. Five-hole probe wind tunnel test set-up for calibration

Fig. 8 shows the test device used in this study. To measure a total of 7 pressure values at the five-hole probe and pitot-tube, a PSI 9016 PRESSURE SCANNER with pressure range of ±1 psi (±0.04% scale error) is used. The pressure values are saved as a text file in a computer.

4.2 Geometry of FHMFP

A five-hole multi-function probe was created based on the results of the configuration design performed previously. A hemispherical configuration pressure probe with a 48° hole position angle and 1 mm hole diameter was established through a comparison of calibration performance by different optimization results and angles. Fig. 9 shows Five-hole probe and pressure port identification. A rectangular jig was added according to the needs of a standard surface in terms of the probe's installation and operation. The total diameter is $\phi 30$ and the total length is about 300 mm.

4.3 Condition of wind tunnel test

Fig. 10 shows definitions of the flow angle and the standard coordinate system. The unknown flow angle can be expressed in two ways as pitch angle and yaw angle, and as cone angle and roll angle. In this study, test data measured through a spherical coordinate system can be expressed in rectangular coordinates through a simple process of coordinate conversion.
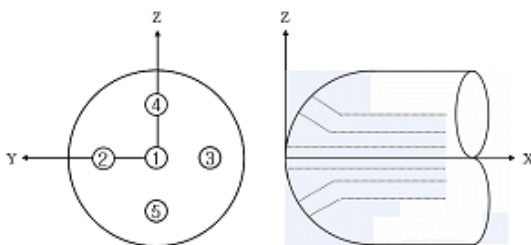

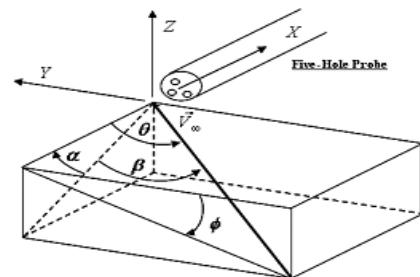Fig. 9. Five-hole probe and pressure port Identification

Fig. 10. definition of coordinate system

The probe installed in the middle of the wind tunnel test device was installed at a flow interval of 10 cm in the X direction to the wind tunnel. The calibration test was performed at a wind velocity of 31 m/s with the cone angle increasing from 0 to 45° at an interval of 5° and with the roll angle increasing from 0 to 360° at an interval of 10°. In terms of the roll angle, to remove the effect of the backlash between the increasing direction and the dwindling direction, the test was performed using the direction of the increasing roll angle.

For each test point, 30 pressure values were obtained for 30 seconds and their average was used. Data used in the test were handled with a calibration technique that uses a multiple regression and mean function.

Calibration Method

5.1 Calibration theory

In present study, calibration is carried out using multiple regression method[5].At each probe hole, pressure coefficients are calculated using following expression,

$$C_{p1} = p_1 - p_0 / P_T - P_0, \tag{7}$$

$$C_{p2} = p_2 - p_0 / P_T - P_0, \tag{8}$$

$$C_{p3} = p_3 - p_0 / P_T - P_0, \tag{9}$$

$$C_{p4} = p_4 - p_0 / P_T - P_0, \tag{10}$$

$$C_{p5} = p_5 - p_0 / P_T - P_0, \tag{11}$$

$$\overline{C}_p = (C_{p2} + C_{p3} + C_{p4} + C_{p5})/4. \tag{12}$$

In above equations, C_P represents pressure coefficient at every hole, P_T and P_o are the tunnel reference pressure measured using pitot tube, and $\overline{C}_P$ is the average of all the pressure coefficients. In probe calibration procedure, two non-dimensional parameters Pitch plane R (upwash) and Yaw plane Q (sidewash) parameters are selected, which are given below,

$$R = C_{Ppitch} = C_{P5} - C_{P4} / C_{P1} - \overline{C}_P, \tag{13}$$

$$Q = C_{Pyaw} = C_{P2} - C_{P3} / C_{P1} - \overline{C}_P. \tag{14}$$

Dynamic and static pressure parameter P and S are defined as follows,

$$P = C_{P5} - \overline{C}_P, \tag{15}$$

$$S = 1 - C_{P5} / C_{P5} - \overline{C}_P. \tag{16}$$

α and β angles are measured, which represents the pitch and yaw angles. However, θ and ϕ angles, which help during the calibration are illustrated in Fig. 10. The relationship between these angles are shown below,

$$\theta = Arc\sin[\sqrt{\sin^2 \beta + \cos^2 \beta \cdot \sin^2 \alpha}], \tag{17}$$

$$\phi = Arc\tan[\frac{\tan\beta}{\tan\alpha}], \tag{18}$$

A relationship between angles and coefficients is as follows,

$$\theta = A_1\sqrt{Q^2 + R^2} + A_2(Q^2 + R^2) + A_3(Q^2 + R^2)^{3/2} + A_4(Q^2 + R^2)^2, \tag{19}$$

$$\phi = B_1\tan^{-1}\left|\frac{Q}{R}\right| + B_2(\tan^{-1}\left|\frac{Q}{R}\right|)^2 + B_3(\tan^{-1}\left|\frac{Q}{R}\right|)^3 + B_4(\tan^{-1}\left|\frac{Q}{R}\right|)^4. \tag{20}$$

Constants A and B are calculated using multiple regression method.

5.2 Application of calibration method

Based on the calibration theory, a calibration technique that converts functions of each section into a single representative function was applied to the calibration test data. The average value of the pressures measured at each test point was calculated by using the cone angle and roll angle, which were then expressed as a single representative function. Fig. 11 shows calibration curve of flow angle vs pressure coefficients, which is the result of applying multiple regressions[5].

To validate the performance of the probe calibrated through the wind tunnel test, a random number table was used to abstract random angle combinations within a cone angle range from 0° to 45° and a roll angle range from 0° to 360°. Fig. 12 and table 3 show results of comparison between measured (the attitude angle) and predicted values using regression method. It is shown that a standard error of ±0.91° was found at a cone angle of 0° ~ 30° and ±2.0° at 30° ~ 43°.
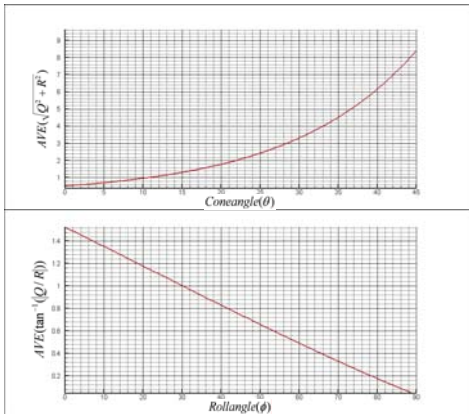

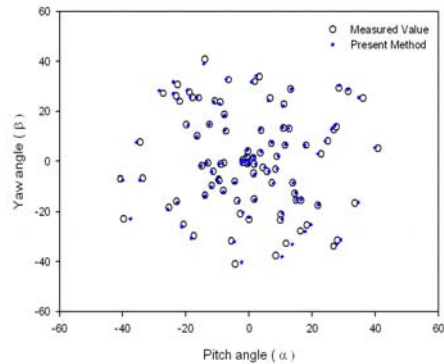Fig. 11. Calibration curve of θ and ϕ vs pressure coefficients

Fig. 12. Comparison between measured and predicted values using regression method

Table 3. Standard errors for the flow angles

	Pitch angle		Yaw angle	
	0 ~ 30°	30 ~ 43°	0 ~ 30°	30 ~ 43°
Cone angle				
Error	±0.89°	±2.0°	±0.91°	±1.8°
Note	[7] Gallington Method : ±2.5°			

Conclusion

This study described a calibration technique for a five-hole, multi-function probe for an air data sensor used in helicopters. For the wind tunnel test, configuration design of the five-hole probe was performed by applying a CFD analysis and an optimization technique; based on the results of the configuration design, a hemispherical five-hole probe with a hole diameter of 1 mm and a hole position angle of 48° was determined to be an excellent air data sensor, and was subsequently fabricated. The created probe was calibrated through a wind tunnel test. The test was carried out by applying a spherical coordinate system of the cone angle and the roll angle. To validate the performance of the probe calibrated through the wind tunnel test, a random number table was used to abstract random angle combinations within a cone angle range from 0° to 45° and a roll angle range from 0° to 360°. Through coordinate conversion, the calibration results using present method and measured values (the attitude angle) were expressed as pitch angle and yaw angle, and compared against each other. The comparison of the calibration results and measured values confirmed that a standard error of ±0.91° was found at a cone angle of 0°～30° and ±2.0° at 30°～43°.

Acknowledgments

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