THE SIXTH ASIAN CONGRESS OF FLUID MECHANICS

May 22-26, 1995, Singapore

発表日 1995年 5月22日 16:30 ~16:45

THREE-DIMENSIONAL VELOCITY VECTOR MEASUREMENT BY FIVE-HOLED PITOT TUBE WITH HOLES SELECTION METHOD

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ABSTRACT In the present paper, a measurement method of three-dimensional velocity vector by fixed spherical five holed Pitot tube with holes selection method is described and this method is applied to 3-D velocity vector measurement with high accuracy. The authors have developed the software for personal computer to realize the above procedures, including automatic calibration system. The standard deviation of measured angles was 0.4 degree for the measurement range of 60 degrees, and 0.8 degree for that of 120 degrees according to a series of test measurement of air flows.

1. INTRODUCTION

A five holed Pitot tube is a probe which can measure inflow angle and flow velocity simultaneously. Measurement method by the tube is categorized into two methods; the balancing one and the fixed one. In the former method, the probe is rotated so that the pressures from the holes are balanced in order to measure the flow direction and the total pressure. This method, however, requires a complex mechanism for the rotation of the probe, which often causes difficulty to install the measurement unit into a given flow field. This made the authors develop the latter measurement scheme, in which the Pitot probe is fixed in the flow. The whole measurement process is fully computerized and divided into calibration and measurement stages. In the calibration stage, the directional characteristics of each hole is thoroughly collected, and the inverse functions are prepared. For the actual measurement, when the Pitot tube is placed in the unknown flow field, the measured pressures from the holes are A/D-converted and taken into a personal computer to process them, in which the velocity vector is calculated through the prepared functions.

In the measurement system of velocity vector in terms of fixed spherical five holed Pitot tube, a series of research has been done[1]. But, if the inflow angle to a hole becomes large, the hole is in the separation region, causing the accuracy of measurement worse. In order to avoid this, the authors propose the "holes selection method", using three highest pressures for the measurement so that the effect of separation is avoided.

2. HOLES SELECTION METHOD AND DIVISION OF REGIONS

The five holed Pitot tube used in the current study is shown in Fig. 1, which has a diameter of 6 mm with 0.6 mm holes and the apex angle of 43°. In the present study, the measurement range with high accuracy is aimed at 60° (divergence angle of 120°). When the flow direction deflects from the probe axis, certain hole(s) can be in the separation region, which causes decrease of accuracy. In order to overcome this problem, the authors have developed a new concept, so called "holes selection method", in which interpolation regions are defined according to flow direction. When the flow direction is close to the probe axis, the five holes are employed in the measurement. On the other hand, when the angle is larger, the holes with highest three pressures are used, which are guaranteed not to be in the separation region.

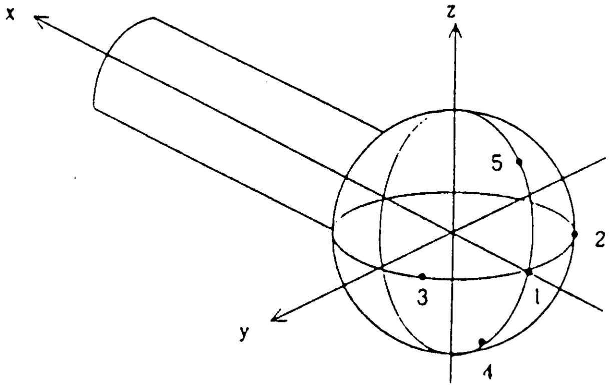


Fig. 1 Five-Holed Pitot Tube

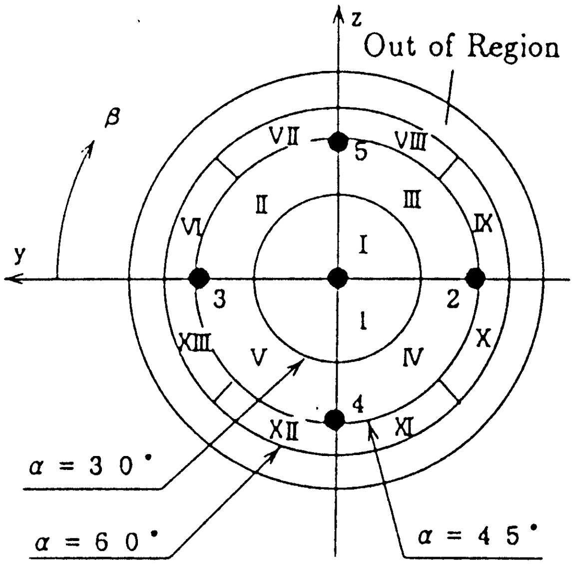


Fig. 2 Division of Regions

The whole range of measurement is divided into 13 sub-regions, as is shown in Fig. 2, and the interpolation function is defined in each region. The polynomial interpolation is thus defined only in a certain region, which makes it easier to attain higher accuracy. The direction of air flow is expressed in terms of α-β system, as defined in Fig. 4. The angle of air flow (α) is less than 30° from the probe axis, 5 holes are used, because all holes are not in the separation region. In the range of α between 30° and 60°, the holes selection method is adopted. This range is first divided into two belt zones of 30° to 45° and 45° to 60°. The inner belt is divided into 4 regions, while the outer belt is divided into 8. These divisions are decided according to the monotoneity of the function in each region.

3. CALIBRATION

3.1 Definition of coordinate system

For expressing a 3-D velocity vector, ξ-γ coordinate system is used, as is shown in Fig. 3. For a better coincidence with the movement of the calibration table, we also used the α-β coordinate system, shown in Fig. 4. If the ranges of both coordinate systems are defined as

$$0^\circ \leq \alpha < 90^\circ, \; -180^\circ \leq \beta < 180^\circ, \quad -90^\circ < \xi < 90^\circ, \; -90^\circ < \gamma < 90^\circ,$$

then, they can be converted each other.

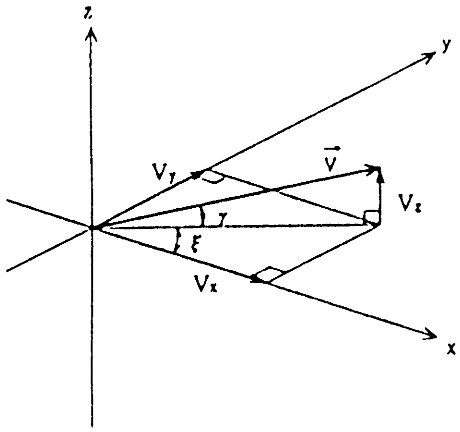


Fig. 3 ξ-γ coordinate system

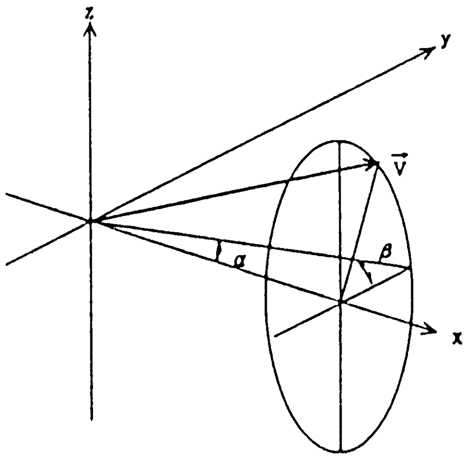
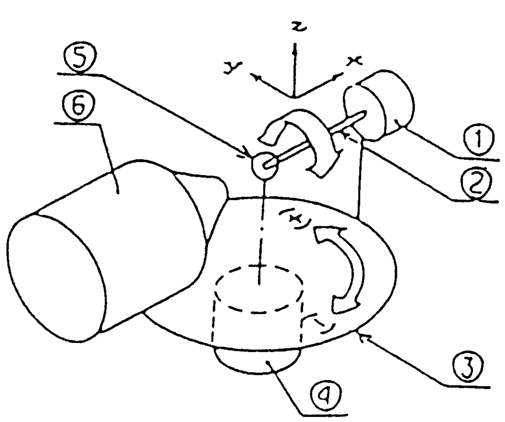


Fig. 4 α-β coordinate system

3.2 Calibration apparatus

Calibration apparatus shown in Fig. 5 consists of a rotating table, a calibration tunnel, an analog differential pressure gauge, pressure control solenoid valves, a personal computer with an A/D converter and parallel output board, driven by the control program[2][3]. Calibration tunnel has a nozzle with a diameter of 40 mm, and the velocity can be changed from 0 m/s to 53 m/s. Total pressure may be measured at the wall inside the calibration tunnel. The pressures at the five holes and the total pressure are measured by a pressure gauge with the operation of the solenoid valves, and they are taken into the personal computer through the A/D converter.



① STEPPING MOTOR2
② PROBE HOLDER
③ ROTATING TABLE
④ STEPPING MOTOR1
⑤ FIVE-HOLED PITOT TUBE
⑥ CALIBRATION TUNNEL

Fig. 5 Calibration Apparatus

3.3 Process of calibration

The pressure ratios, X_j, Y_j (j=I ~ XIII, j being region number), which are related to inflow angles, are defined at each sub-region. The formulation of the pressure ratios at I; the central region, II; the inner belt zone, and XI; the outer belt zone are as follows.

$$X_{\mathrm{I}} = (p_{z2} - p_{z3}) / \{p_{z1} - \mathrm{MIN}(p_{z2}, p_{z3})\}, \quad (1)$$
$$Y_{\mathrm{I}} = (p_{z4} - p_{z5}) / \{p_{z1} - \mathrm{MIN}(p_{z4}, p_{z5})\}, \quad (2)$$
$$X_{\mathrm{II}} = p_{z1} / \sqrt{(p_{z1}^2 + p_{z3}^2 + p_{z5}^2)/3}, \quad (3)$$
$$Y_{\mathrm{II}} = (p_{z3} - p_{z5}) / \sqrt{(p_{z1}^2 + p_{z3}^2 + p_{z5}^2)/3}, \quad (4)$$
$$X_{\mathrm{XI}} = ((p_{z1} + p_{z3} + p_{z5})/3) / \sqrt{(p_{z1}^2 + p_{z3}^2 + p_{z5}^2)/3}, \quad (5)$$
$$Y_{\mathrm{XI}} = p_{z5} / \sqrt{(p_{z1}^2 + p_{z3}^2 + p_{z5}^2)/3}. \quad (6)$$

Here, p_{zi} is the pressure difference at the ith hole based on the standard pressure p_0, which is the atmospheric pressure p_a in the current study. MIN denotes to take the smaller value. Pressure ratios on the other sub-regions are defined in a similar manner as for the corresponding belt zone. The pressure coefficient, C_{pi}, which are related to flow velocity, is defined for each hole (i=1,..,5) as follows.

$$C_{pi} = p_{zi} / \frac{\rho}{2} V^2, \quad (7)$$

where ρ is the fluid density.

According to the above defined coefficients, the calibration process is carried out in the following manner. The Pitot tube is inserted in the air flow whose velocity V is constant. A set of pressure data p_{zi}'s is measured at each sampling point, which is the prescribed inflow angle α and β. Thus the relation between the pressures and the inflow angle is obtained over the whole range of the measurement. By the least square method, the angles of the flow velocity, ξ and γ, which are converted from α and β, are expressed as the polynomial function of the pressure ratios, X_j and Y_j, as

$$\xi = F_{\xi j}(X_j, Y_j), \quad (8)$$
$$\gamma = F_{\gamma j}(X_j, Y_j). \quad (9)$$

In the same way, the pressure coefficients are also formulated by polynomial function, as

$$C_{pi} = F_{Ci}(\xi, \gamma). \tag{10}$$

Thus, the characteristics of the Pitot tube are expressed as polynomial functions.

The range of Reynolds number, R_e, for the measurement is in the range of $4.0 \times 10^3 < R_e < 1.5 \times 10^5$, where flow around a sphere is stable and pressure ratios and pressure coefficients are independent of R_e[4].

4. MEASUREMENT

The first step in the measurement of 3-D velocity vector is to find the region which the inflow angle belongs to. A non-dimensional number is defined to judge the region, which approximately depends only α and is independent of β. The pressure ratios X_j and Y_j at the corresponding region j are calculated from Eqs. (1)~(6), then inflow angles ξ and γ are calculated by substituting X_j and Y_j into Eqs. (8) and (9). By defining the hole number with the maximum pressure being m, the pressure coefficient C_{pm} is calculated from ξ and γ by applying Eq. (10). Then the absolute flow velocity V is obtained by

$$V = \sqrt{2p_{zm}/\rho C_{pm}}. \tag{11}$$

Thus, the velocity vector of the air flow is obtained.

5. TEST MEASUREMENT OF VELOCITY VECTOR

Measurement points of velocity vector are determined at an interval of 5° in α direction from 0° to 60° and at an interval of 45° in β direction from -180° to 135°. The angle of inflow to the tube is adjusted also by the calibration table, shown in Fig. 5. When the range of α is $0° \leq \alpha \leq 30°$, the standard deviation of the measured angle was 0.4° and the error of the measured velocity was 0.7 % by using pressures at five holes. When the range of α is $30° < \alpha \leq 60°$, the standard deviation of the measured angle was 0.8° and the error of the measured velocity was 0.8 % by using holes selection method. But 4.9° and 2.6 % respectively by using pressures of the five holes over the whole region. Thus the superiority of holes selection method was confirmed.

6. CONCLUSION

Authors developed a measurement method of three-dimensional velocity vector by spherical five holed Pitot tube with holes selection method. The main results of the research are as follows.

1) Authors established the holes selection method which do not use the pressure in the separating region when an inflow angle is large.
2) It is possible to measure the three-dimensional velocity vector in high accuracy by using holes selection method.
3) The maximum standard deviation of measured angle was 0.8 degree for the measurement range of 120 degrees according to the test measurement.

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