Design and Calibration of Five- Holed Conical Probe for Fluid Velocity Measurements in Three Dimensions

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Summary

The performance of a five-holed conical probe (which has a conical head with four holes symmetrically placed on the cone surface and one at the truncated tip) for the measurements of fluid velocity in three dimensional incompressible flow was investigated in air in an open circuit subsonic wind tunnel . The air velocity ranged from 15 – 45 m/s and the Reynolds number ranged from 40000 to 100000 based on the cone base diameter. The methods of calibration and use of the probe are given where the measurements of one angle and three pressures are sufficient to give the three components of velocity, static and total pressure. The conical head probe is easier to manufacture than the spherical head probe and has the advantage of having clear fluid separation points at the cone base whereas the fluid separation on the spherical probe is not well defined and depends on the Reynolds number.

تصميم و معايرة مجس مخروطي خماسي الثقوب لقياس سرعة المائع في الآبعاد الثلاثة

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الخلاصة

أن أداء المجس المخروطي ذا الثقوب الخمسة والتي تكون أربعة منها موزعة بالتناظر على سطح المخروط بينما الثقب الخامس يقع على قطع في رأس المخروط والذي يستعمل لقياس السرعة في المائع غير القابل للضغط قد أجري في نفق هوائي ذي سرع تحت الصوت من 15 – 45 m/s ولمدى لرقم رينولدز من (100000 - 40000) باستعمال قطر قاعدة المخروط . ويعطي البحث هنا كيفية استعمال وتعيير المجس حيث يكفي قياس زاوية واحدة وثلاثة ضغوط للحصول على مركبات السرعة الثلاثة والضغط السكوني والضغط الكلي .

أن تصنيع المجس المخروطي أسهل من المجس الكروي وكذلك أنفصال الما ئع يكون محددا عند قاعدة المخروط بينما في المجس الكروي مكان انفصال المائع لا يكون محددا ويعتمد على رقم رينولدز

1- Introduction

In many applications of fluid mechanics it is necessary to measure the static and total pressure together with the three components of velocity. One of the early designs was a spherical probe [1] with five symmetrically distributed holes . Porro [2] patented a design where fine tubes were soldered and machined to form a pyramidal tip with five holes . The conical probe with 4 or 5 holes was investigated and used [3,4] with great success .

It may be helpful to comment on the differences between the spherical and conical types of probes.

- **a- The conical shape is easier to manufacture accurately**
- **b- The cone angle may be chosen**
- **c- The separation point (of the fluid from the surface) is defined for the cone but for the sphere it is not fixed and its place depends on Re number and surface roughness.**

The five holed conical probe was used successfully for multi phase flow [5,6] .

The probe was also used extensively in turbo-machine research [7] and in supersonic flow measurements [8] . Cambridge University has dedicated a website to the research on these probes [9] . Finally there were accurate measurements made by this five holed conical probe for a space vehicle simulated in a wind tunnel [10] .

2- Static Pressure Distribution on the Cone Surface

The static pressure distribution on the surface of a cone with a truncated tip was found experimentally by tests in a subsonic air wind tunnel . The Re number range ,based on the diameter of the cone base, was between 40000 to 100000 and showed no noticeable effects.

Experiments were performed on a cone of tip included angles of 40 with five holes (tappings) on the side surface of the cone. The holes were at different positions and different values of r and the pressure distribution was found for different angles of yaw β as shown in Fig (2).

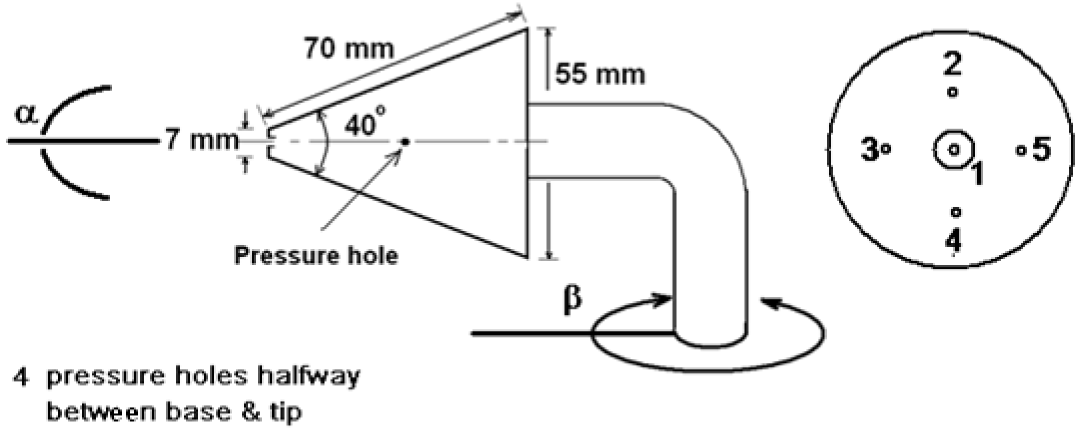

Fig (1) Prototype probe details

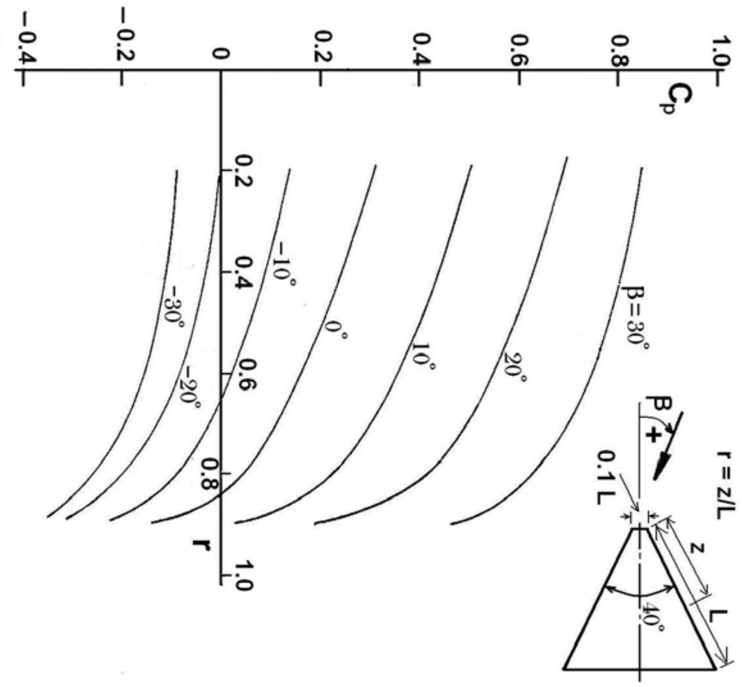

Fig (2) Pressure distribution on cone surface

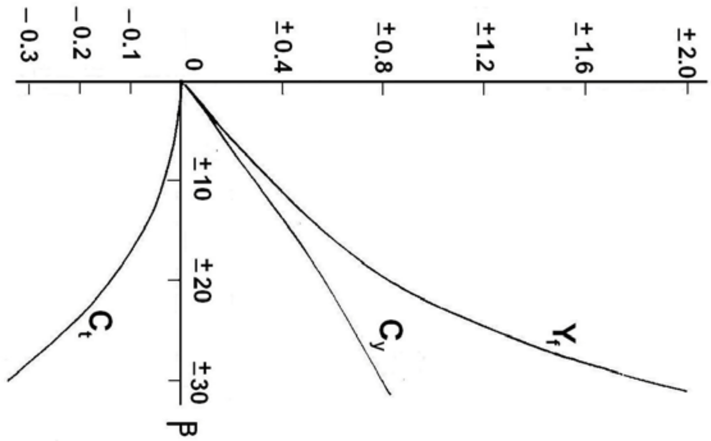

Fig (3) Probe coefficients vs. Yaw angle

The static pressure coefficient C_p which is defined by the equation :

$$C_p = (p_{surface} - p) / 0.5 \rho V^2 \text{---(1)}$$

where $p_{surface}$ is the pressure on the cone surface and P is the free stream static pressure.

C_p is shown plotted in Fig.(2) for various angles of yaw (the angle of yaw is defined as the angle between the flow direction and cone axis when the pressure hole lies in their plane).

The static pressure distribution is helpful in choosing the optimum position of the pressure hole .

For example taking the curve $\beta = 0$ in Fig. (2) the position of the pressure hole should be chosen at minimum values of $(\partial P/\partial r)$

This should be done to insure that an error in hole positioning will give the smallest error in pressure reading. It is seen from Fig.(2) that holes should not be made close to the base of the cone . The recommended position would be between $0.3 < r < 0.6$

Premilinary experiments with cones of included angles 24, 40 , 60 and 80 degrees showed that C_p and $(\partial P/\partial r)$ increased slightly with increasing cone angle for zero yaw angle tests .

The 40 degree angled cone was chosen for the subsequent investigation

The cone was made on the lathe machine from brass as shown in Fig, (1).

The included angle was 40 and there were 4 holes on the side of the cone situated midway between the cone base and the truncated tip.

3- Yaw and total Pressure

The yaw coefficient C_y which is defined by the equation :

$$C_y = (P_3 - P_5) / 0.5 \rho V^2 \text{ --(2)}$$

P_3 and P_5 represent the pressures on two opposing holes which are symmetrically placed and lie in the same plane as the cone axis and flow direction.

The total pressure coefficient is defined by the equation:

$$C_t = (P_1 - P_o) / 0.5 \rho V^2 \text{ ----(3)}$$

P_1 is the pressure measured by the front hole at the truncated tip of the cone . P_o is the actual total pressure . P_1 is always less then P_o except at zero yaw angle where they are equal.

The above mentioned coefficients C_y , C_t and Y_f which are calculated from equations (2 , 3 and 4) are shown plotted in Fig.(3)

4- Calibration Procedure

In order to define a yaw coefficient in a three dimensional flow field , where the velocity , static and total pressure are unknown , a yaw factor Y_f is defined as follows :

$$Y_f = (P_3 - P_5) / \{ P_1 - 0.5 (P_3 + P_5) \} \text{ ----------------------(4)}$$

This coefficient and the full calibration curves of the probe are given in

Fig.(3) .

The calibration would take the following steps:

a- P_1 , P_3 and P_5 are measured.

b- Y_f is found from equation (4)

c- β , C_t and C_y are found from the curves in Fig.(3)

d- The undisturbed velocity V is calculated from equation (2)

d- P_o (the total pressure) is obtained from equation (3) .

e- The static pressure P is obtained from equation (5)

The following steps are taken in order to get :

a- The three components of velocity

b- The static pressure

c- The total pressure

(1) The probe is arranged so that its axis is in the X- direction ,holes 3 and 5 in the Y- direction and holes 2 and 4 in the Z- direction as shown in Fig.(4a , the front view) where V_{xy} is the projection of the velocity vector V on the xy plane. In fig. (4b , the top view) the projection of V is V_{xz} on the xz plane making an angle α with the X- axis.

(2) The probe is rotated about the Y- axis until the pressures P_2 and P_4 become equal so that the new x direction becomes $x^/$. This measured angle is α as shown in fig. (4c)

(3) The pressures P_3 , P_5 and P_1 are measured

(4) Y_f is obtained from equation (4)

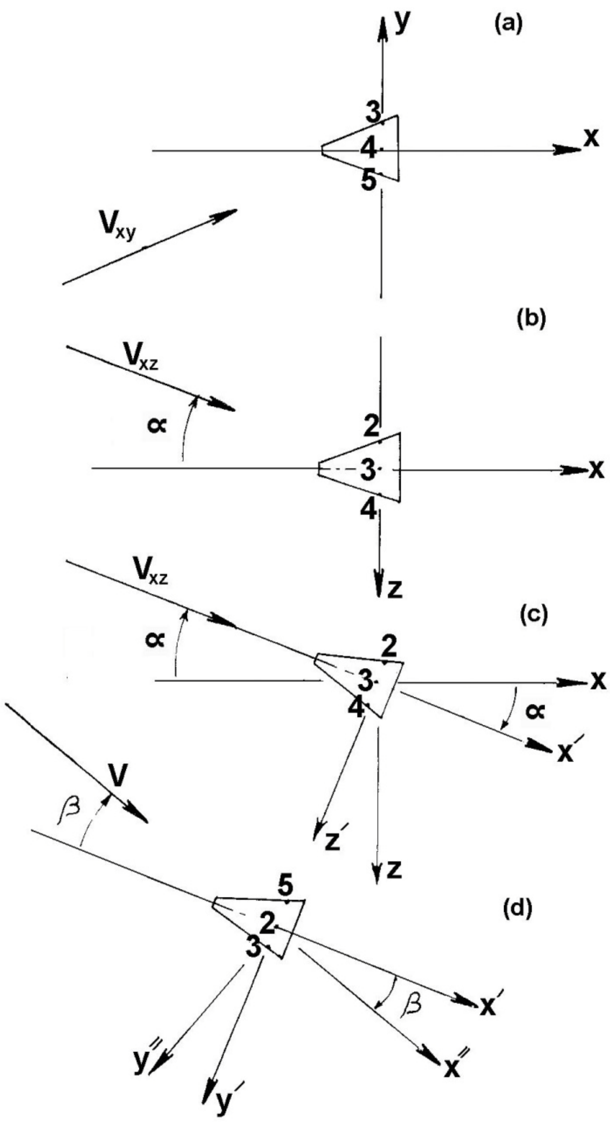

Fig (4) Axes rotations for 3-dimensional measurements

(5) From Fig. (3) the values of C_y , C_t and β are obtained.

(6) The velocity vector V is obtained from equation (2) .

(7) The total pressure P_o is obtained from equation (3)

(8) The static pressure is obtained from the relation :

$$P_o = P + 0.5 \rho V^2 \qquad \text{----(5)}$$

(9) It can be observed that there are two rotations for the velocity vector V to coincide with the $x^{//}$ one through angle α and then another at angle β (changing the axes from x to $x^{/}$ to $x^{//}$ and also for y to $y^{/}$ to $y^{//}$ and z to $z^{/}$ to $z^{//}$ axes) . The three components of the velocity vector in the xyz system may be calculated by geometry or by using the tensor transformation for rotation as shown below :

$$\begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} V \\ 0 \\ 0 \end{pmatrix}$$

Solving the above equations the components are obtained :

$V_x = V \cos\alpha \cos\beta$
$V_y = V \sin\beta$ and
$V_z = V \sin\alpha \cos\beta$

5- Discussions & Conclusions

a- The conical probe has advantages over the spherical one. This is because it has well defined separation points at the cone base whereas the separation points for a spherical probe depend on Re and surface roughness as is well known in general fluid mechanics.

b- The calibration curve which are presented in this paper should be useful for accurate measurements of the fluid velocity in three dimensional flow fields giving the three components together with the total and static pressure.

c- The conical probe is easier to manufacture and with better accuracies in the dimensions and cone angle than manufacturing a spherical probe

d- The optimum positions of the holes can be chosen based on the pressure distribution on the surface of the cone which was obtained from tests in a subsonic wind tunnel.

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