STATIC PERFORMANCE CHARACTERISTICS OF VORTEX RATE SENSOR

Dr .Ali Abdul AL-Muhsen AL-Asady
Asst .prof. Dept .of Mech .En
Baghdad University

Wisam Gasim Kadhum
Dept.of Mech .Eng.
Baghdad University

ABSTRACT

The vortex rate sensor is a fluidic gyroscope with no moving parts and can be used in very difficult conditions like radiation, high temperature and noise with minimum cost of manufacturing and maintenance. A vortex rate sensor made of wood has been designed and manufactured to study theoretically and experimentally its static performance .A rig has been built to carry out the study, the test carried out with three different air flow rates (100, 150, and 200 l/min).The results show that the relation between the differential pressure taken from the sensor pickoff points and the angular velocity of the sensor was linear.The present work involved theoretical and experimental study of vortex rate sensor static characteristics .Vortex rate sensor has been designed and manufactured with dimensions-:

Radius of vortex chamber= 140 mm, Radius of sink tube r_s= 4.5 mm, the pickoff hole diameter = 2mm, Height of vortex chamber b= 19 mm, Height of pickoff pipe h= 25 mm.

Keywords :Vortex rate sensor, Angular vortex rate sensor, Rate gyro

الخلاصة:

متحسس معدل التدويم هو جايروسكوب مائعي بدون اجزاء متحركة ويمكن استخدامه بظروف صعبة جدا كالاشعاع ودرجات الحرارة العالية والضوضاء وبأقل كلفة تصنيع وصيانة. متحسس معدل التدويم مصنوع من ماده الخشب تم تصميمه وتصنيعه واستخدامه لوضع دراسة نظريه وعمليه للأداء الاستاتيكي للجهاز. كذلك تم بناء منظومة خاصة لإجراء الدراسة، في هذه الدراسة تم تسليط ثلاثة قيَم مختلفة لمعدل تدفق الهواء وهي (١٠٠،١٥٠ و ٢٠٠ لتر\دقيقه) ووجد من خلال هذه الدراسة ان العلاقة ما بين فرق الضغط المأخوذ من الجهاز والسرعة الزاوية للجهاز هي علاقة خطيه.يتضمن هذا البحث دراسه نظريه وعمليه للخواص الاستاتيكيه للمتحسس . حيث تم تصميم وتصنيع المتحسس بالابعاد التاليه:

نصف قطر حجرة الدوامه(R)=١٤٠ ملم ، نصف قطر مجرى الخروج (r_s)=٤،٥ ملم،قطر فتحه الpickoff=٢ملم، ارتفاع حجرة الدوامه (b)=١٩ملم، ارتفاع انبوب pickoff (h) =٢٥ ملم.

INTRODUCTION

General introduction

The vortex rate sensor is a pure fluidic device with no moving parts that senses angular velocity about its axis and provides a differential pressure proportional to that velocity it can be used instead of a gyroscope .The three basic parts of the sensor are the coupling element, the vortex chamber, and the signal pickoff .The vortex rate sensor utilizes the tendency of the swirling flow to conserve the angular momentum imparted to it as a means of amplification to sense small rates of rotation . The existing vortex rate sensor consists of two coaxial disks separated by cylindrical coupling ring, which are often a porous material, with outlet sinks and two suitable pickoffs .The gaseous fluid flows through the coupling element of uniform length and porosity and discharges at the sink tube .The radial flow between the two coaxial disks is modified by the viscous shear and by the vertical flow created by the rotation of the unit about an axis parallel to its axis of symmetry .Thus, the confinement of the real flow and the subsequent modification of the velocity distribution in the sink tube cause appreciable reduction in the angular momentum imparted at the coupling . Attention is given to sensitivity, accuracy, and response time and to sensor design and fabrication with emphasis on housing and manifold, null adjust and built-in test and temperature compensation .A number of applications of the vortex rate sensor are considered :aircraft flight controls, ejection seat stabilization, and helicopter gun turret stabilization.

Various analyses have been carried out in the past with varying degrees of success and different specific objectives on vortex rate sensor.

[Organ H.D. 1965] changed the porous with cylindrical outer screen member and inner cylindrical screen member has a slightly smaller diameter than outer screen member . Positioned intermediate inner screen member and outer screen member are a plurality of glass balls having a small diameter approximately (0.15) It is clear that coupling means is porous in nature and allows fluid to pass through with a minimum of restriction.

[Barrete Doyle 1966] made vortex rate sensor with the same geometry but with another kind of pickoff, this kind includes optical means for providing an output signal indicative of the rotation of coupling relative to the structure .Optical means comprises a light source and two reflecting mirrors attached to intermediate light source and reflecting surface .A pair of photocells is attached to contiguous mirrors.

[Camarata F.J. 1969] Invented a twin vortex rate sensor .The invention contemn plates the provision of two counter-moving or rotating vortices, each having its axis or center line coincident with the axis about which movement of the body is to be sensed . The output flow or pressure of each vortex is compared with that of the other, and the differential of such output pressure or flows provides a signal indicative of the rate and direction in which a body containing such vortices is turning on the said axis .Thus, it will be seen that this applicant provides a device generally similar in function to a gyroscope, and it can be said that it is general object of this applicant to provide a device capable of sensing the rate and angular direction of movement of a body about a reference axis and capable also of producing a signal indicative of rate and direction so that the signal can be used in control of angular movement of the body.

[Hagiwara, etal.1973], studied the static characteristics of vortex rate sensor .A sensor probe is constructed of two stagnation pitot tubes whose setting gap and angle are determined to be 3.6 mm and 67.5 deg . respectively for a sink tube with inner diameter of 8 mm by the preliminary experiments .In case of 100 *l*/min supply, output signal is 8.3 mm water per r.p.m and is linear up to 10 r.p.m for a sensor with the outer diameter of 280mm.Sensor efficiency is deduced theoretically and the results of the analysis are verified to coincide very well with the experimental results.

[Peter Norton 2006] invented a vortex angular rate sensor for measuring yaw rate or roll rate of an automotive vehicle comprises a freely rotating inertial disk and an angular rate sensor responsive to the rotation of the inertial disk relative to housing .In one embodiment the inertial disk presents an alternating magnetic field at its circumference .The rate and direction of rotation of the inertial disk relative to its housing is determined by three magnetic field sensor such as a linear Hall Effect sensor responsive to the field presented by the inertial disk .In another embodiment electronic cameras measure movement of fiducially marks on the inertial disk .Air surrounds the inertial and air viscosity gradually brings rotation to a stop .For yaw rate measurement the disk axis is oriented vertically and the inertial disk is supported in the radial direction by low friction bearing such as ball bearing or magnetic bearings and the axial direction by substantially frictionless bearing such as magnetic bearings .In certain embodiments two magnetic poles operate as both axial and radial bearings .For the purpose of sensing incipient or actual vehicle rollover, the axis of the inertial disk is oriented in the direction of the roll axis of the vehicle .The angle of recent rotation and rate of rotation of the inertial disk relative to the housing indicate the angle through which the vehicle has recently rotated about its roll axis and the roll rate of the vehicle .

GEOMETRY OF THE SENSOR AND MEASURING CIRCUIT

The sensor shown in the fig.1 made of wood type (NDF) for ease of machining.

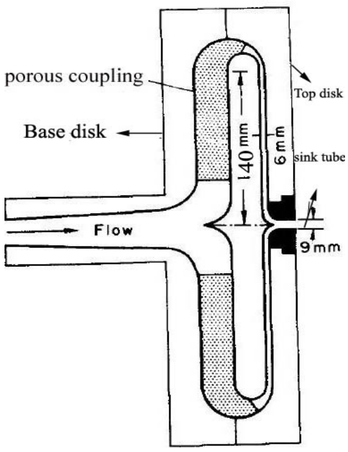

Fig.1 Schematic Drawing of vortex rate sensor

A series of slices and porous media made of sponge was inserted in the inlet region partly the purpose of the porous media and a slices were partially to ensure uniform flow at the periphery of the pancake.A single hole of 9mm diameter was drilled at the center line of the outer disk; a sink tube was fitted into this hole and tightened on the outer disk .The pickoff tube used at the exit of the sink tube called cylindrical pickoff tube as shown in **fig.2** placed across the sink tube.

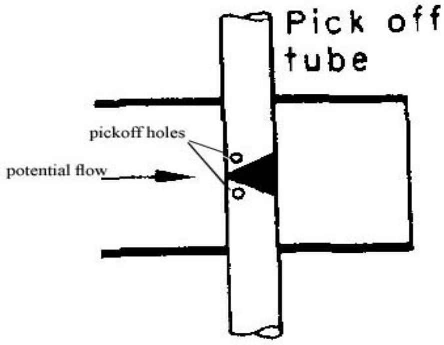

Fig.2 Schematic of Cylindrical Pickoff Element

The pickoff hole was positioned at 45 degree from the direction of flow in order to obtain maximum theoretical differential pressure across them .A straight forward analysis of potential flow about circular cylinder shows that whereas the rate of change of pressure with angular position is maximum at θ=45 degree .**Fig.3** shows the test rig, its consist of compressor to supply air, rotameter to measure the air flow rate and control it ,vortex rate sensor and pick off element, see **fig.4**, rate table for control and apply the angular velocity see **fig.5**, and U tube manometer to measure the output signal of vortex rate sensor

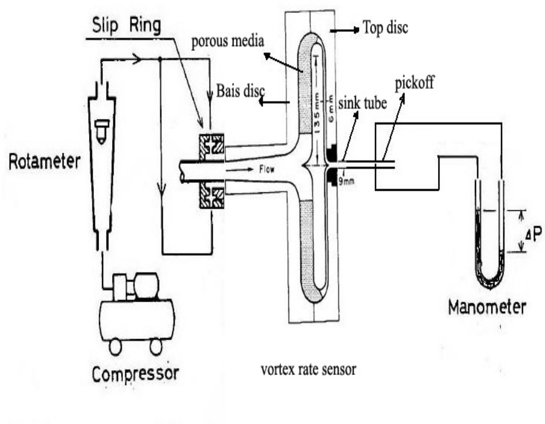

Fig.3 testing rig

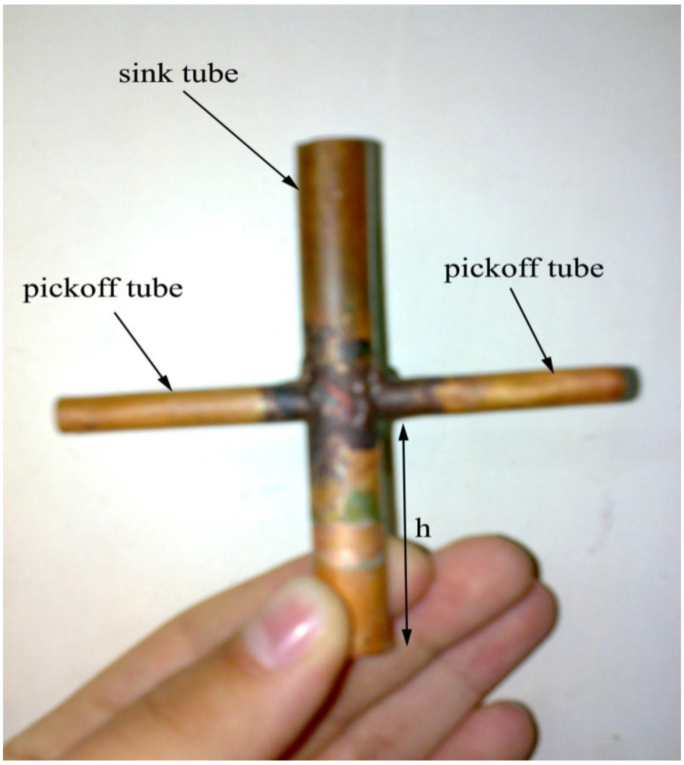

Fig.4 pickoff tube used in the test rig

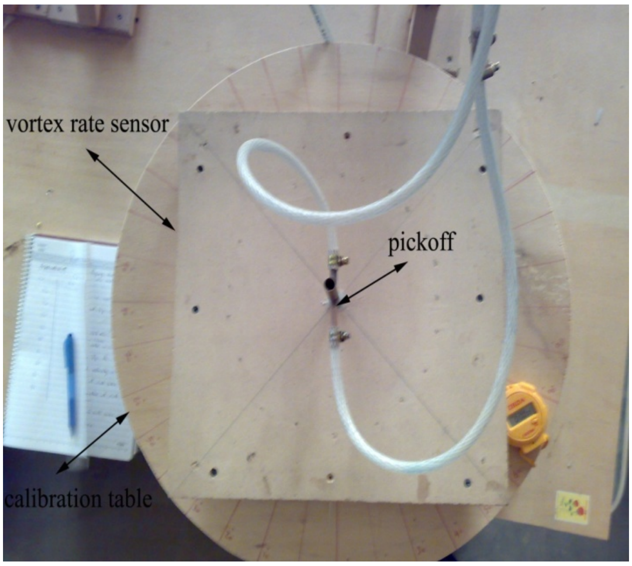

Fig.5 Calibration Table of vortex rate sensor

ANALYSES OF THE SENSOR OUTPUT

The principle work of pickoff element like the principle work of Pitot tube, because both of them determine the pressure at stagnation point(pickoff holes, pitot hole) which it's one of the application of Bernoulli's equation .It follow from Bernoulli's equation that the pressure at stagnation point (total pressure P) is equal to the sum of the static pressure (P = 0) the dynamic pressure ($\frac{\rho U^2 \sin^2\theta}{2}$) of the flow .Apply the following assumption:

1. Neglect the viscosity (invisced) i.e$\left(\upsilon\nabla^2 V\right)$ .Is small, because the boundary layer is small compared with the chamber height.
2. The flow is incompressible (M< 0.3)
3. Neglect the body force (g=0).
4. Steady state.

The pickoff holes are set at angle **θ** against the sink tube axis and those holes are located at symmetrical distance – r_p and +r_p from the center of sink tube respectively .If the vortex rate sensor is stationary and supply flow rate is constant, the detecting pressures of pickoff holes (P1 = P2).

$$P_1 = P_2 = 0.5\rho\beta^2 U^2 \sin^2\theta \qquad (1)$$

Eq. (1) represents the pressure distribution at pickoff hole when the vortex rate sensor is stationary .Where :
(β=1.12 for turbulent distribution flow) **[Pavila, C. 1972]**.

As the vortex rate sensor rotates with angular rate ω_m, the jet from sink tube develops into spiral flow with the spiral angle Δθ .The differential pressure Δp between the pickoff holes (1) and (2) is produced.

$$P_1 = 0.5\,\rho\,\beta^2\,U^2_s\,\sin^2\theta_1 \text{ for pickoff hole} \qquad (2)$$

$$P_2 = 0.5\,\rho\,\beta^2\,U^2_s\,\sin^2\theta_2 \text{ for pickoff hole} \qquad (3)$$

$\Delta p = P_1 - P_2$ sub Eqs(2) and (3) that leads to:

$$\Delta p = 0.5\rho\beta^2 U_s^2 \Delta\theta \qquad (4)$$

Where $\Delta\theta \approx (\sin^2\theta_1 - \sin^2\theta_2)$

Noting that the swirling angle, resulting from the tangential velocity of fluid relative to the tangential velocity of pickoff hole; is given by **[Camarat, F. J 1996].**

$$\tan\Delta\theta = \frac{(U_{\theta rp} - r_p w)}{\beta U_s} \qquad (5)$$

$$\Delta\theta = \frac{U_{\theta rp}}{\beta U_s} \qquad (6)$$

Where $U_{\theta rp}$ is the maximum tangential velocity at radius $\mathbf{r_p}$ in sink tube, and that equal to:

$$U_{\theta rp} = \frac{E_2 \omega R^2}{r_p} \qquad (7)$$

r_p is The radial distance to the location of the pickoff hole which is also the radius where the tangential velocity is maximum.

$E_2=\Gamma_p$,Γ_0= 0.716**[pavilan. C.1972].**

Sub eq (7) in (6) and then in eq (8) we obtain:

$$\Delta p = 0.5\rho\omega\beta E_2 U_s \left(\frac{R^2}{r_p} \right) \qquad (8)$$

The maximum tangential velocity occurs at a radial distance ranging from $0.3\,r_s$ to $0.4\,r_s$

Multiplying eq (8) by $(\frac{Q}{Q})$

r_s: the radius of sink tube .

Thus, writing :r_p=J .r_s

Where; J=const=0.376 **[peter Norton, 2006].**

Q=π. r^2_s. U_s then eq (8) is:

$$\Delta p = 0.34\left(\frac{\rho\omega Q}{r_s} \right)\left(\frac{R}{r_s} \right)^2 \qquad (9)$$

It is evident from eq (9) that the differential pressure signal increases most rapidly with degreasing sink tube radius, secondly with increasing sensor radius, and thirdly with increasing rate of rotation, flow rate and fluid density.

The standard deviation for the eq. (9) between the theoretical and experimental results for (10) points curve at 100 l/min air flow rate is calculated as below;

$$\text{Standard deviation} = \frac{\sqrt{\dfrac{\sum(\delta(\Delta p))^2}{N-1}}}{\sqrt{N}} \qquad (10)$$

Where; N is the number of the corresponding points.

The standard deviation = 2.01108 mm water.

Obviously, there is a limit to the magnitude of each one of these parameters .The size of the pickoff element that in turn is limited by manufacturing difficulties, the flow rate is limited by the capacity of the available power source.

TEST PROCEDURE:

To collect and explain the relation between (Δp) and (ω) (static characteristics of vortex rate sensor) should follow the procedure bellow:

1) Turn on the compressor and start to press the air inside the container of compressor.
2) Open the valve of the rotameter and fix the float off on the flowmeter (50 L/min) firstly.
3) Before applying the angular velocity to the vortex rate sensor see that the signal in the differential manometer is zero.
4) Apply angular velocity started from (10, 20, 30, 40, 50, 60, 70, 80, 90) deg/sec respectively with no change in the value of the flow rate.
5) In each angular velocity has been applied on the vortex sensor, there is a signal produce as differential pressure measured in (mm water) on the differential manometer.
6) After that repeat the procedure again but with another flow rate (100, 150, 200) L/min respectively.

RESULTS AND DISCUSSIONS:

The experiment that carried out for vortex rate sensor with this dimensions (Radius of vortex chamber (R)=140 mm , Radius of sink tub r_s= 4.5 mm, pickoff hole diameter =2mm , Height of vortex chamber (b)=

19mm, Height of pickoff pipe (h) =25 mm). Fig.6 shows the static characteristics theoretically for various flow rate and angular velocities .Note from Fig.6 that the linearity of vortex rate sensor keep in linear for ω=90 degree/sec and the Δp increases when increase the angular rate ω and when increase the flow rate of the input. Fig.7 shows the results of the vortex rate sensor experimentally for various flow rates and angular velocities .The range of linearity of signal obtained from cylindrical pickoff element was limited to approximately 70 deg/sec as shown in Fig.7 .This was in part due to the fact that the total velocity vector in the vicinity of the pickoff element was not in the plane normal to the cylinder, in the part due to the constricting effect of pickoff element which in turn altered the velocity profile and accelerated the flow, and in part due to the separation and vortex shedding behind the cylindrical coordinates .Fig.8 shows comparison between experimental and theoretical static characters and shows the relation between the differential pressure and angular velocity .It is, however; apparent from a cursory examination of the data presented here, the cylindrical pickoff yields a differential pressure output very good. So the output remains linear up to an angular velocity of approximately 70 deg/sec .This is partly due to the fact that the swirling flow has not been distributed by cylindrical pickoff and that the signal transition line has resulted in relatively more stream lined body there by significantly eliminating the flow separation , vortex shedding and noise.

There are many reasons that effect on the relation between the differential pressure and angular velocity:

1. Experimental errors (like stop watch, calibration table.)
2. The effect of viscosity on the swirl and flow in the sink tube.
3. The effect of the porous media and slices and several other secondary effects lead to reduce The efficiency.

The linearity of the vortex rate sensor to the differential pressure or between Δp and ω is also calculated from measuring the maximum input deviation and the maximum full scale input:

$$\text{Non-linearity} = ((\text{max. input dev.})/(\text{max. full scale input}))*100 \qquad (11)$$

The non-linearity of the sensor is 5%, and form **fig.7** the curves make a line with a regression factor **0.9955** so we can say that the vortex rate sensor is linear to differential pressure Δp.

Resolution is the smallest measurement a sensor can reliably indicate .The resolution of the vortex rate sensor is 9 mm water differential pressure.

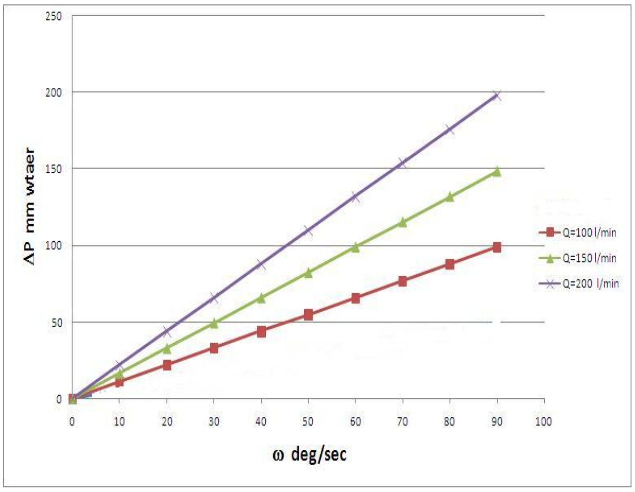

Figure.6 Theoretical Static Characteristics.

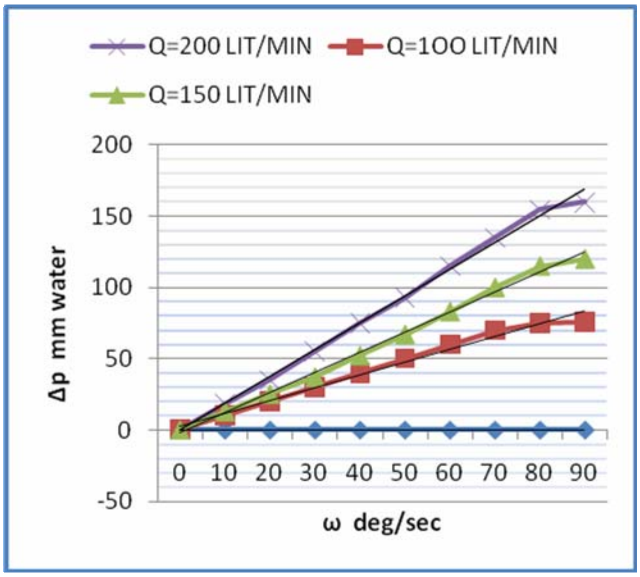

Figure.7 Experimental Static Characteristics.

CONCLUSIONS:

The static performance characteristics of vortex rate sensor are presented in fig (6, 7 and 8).from the figures it can be concluded that relation between the differential pressure and angular velocities is linear and the sensitivity of the instrument is increases as the flow rate increase.

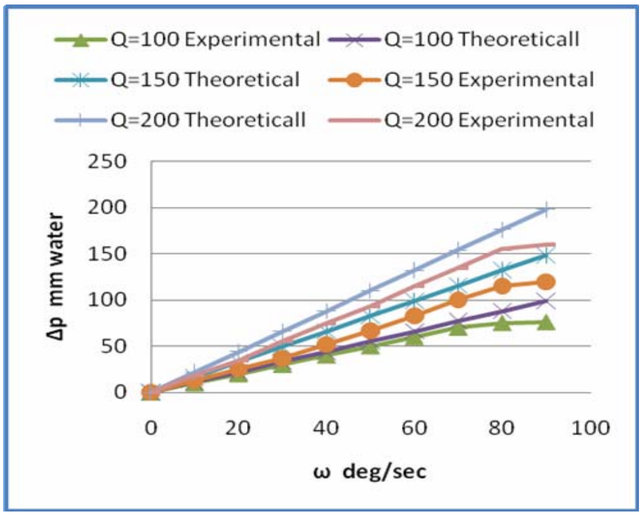

Figure.8 Comparison between theoretical and experimental static characteristics.

REFRENCESES

Barrett Doyle, “Vortex Rate Sensor", U.S Patent 3,240,060 (Mar 1966).

Camarata, F.J.”Twin vortex angular rate sensor”, U.S patent 3,447,383 (June 1996)

Foster. K .&Parker, G.A,"Fluidics Components and Circuits", McGraw-Hill Company, 1970

Ogren .H .D, “vortex rate sensor” ,U.S patent 3,203,237 (Aug 1965).
Aeronautics and Space A demonstration, Washington, D.C, July 1969.

Paviln..,”Theoretical Analysis of Angular Momentum Conservation and Signal Transition in a Constant Speed Rate Sensor", Journal of fluid mechanics, Vol.8, pp 433-443, pergamon presses 1972.

Peter Norton, "Angular Rate Sensor ", U.S Patent 7,132,936 B1, (Nov 2006).

Sarpkaya. T, "A Theoretical and Experimental Study of Vortex Rate Gyro", advance in fluidics, ASME, 1967.

.Sarpkaya.T,"A Pneumatic Vortex-Angular Rate Sensor-Analysis and Experiments", second IFAC symposium on fluidics, Vol.9, pp.29-34, pergamon press, 1973.

Tatsaya, Chiaki Iwadare,”On a vortex angle ratesensor” J.S.M.E, vol.12, no.7, 1973

Wilton P .Lock and Sbu W.Gee, "Flight Investigation of A Fluidic Auto Pilot System", National

Tatsuya Hagiwara, Shoji Kamimura and Chiaki Iwadare. "On A Vortex Angular Rate Sensor", J.S.M.E, Vol.12, No.7, 1973.

NOMENCLATURE

SYMBOL	**MEANING**
E_2	viscous efficient within sink tube
G	Acceleration due to gravity (m/ s^3)
M	mach number
P	Pressure distribution for potential flow across cylinder (mm water)
R	The effective radius of vortex rate sensor (mm)
r_p	The radial distance to the location of the pickoff hole (mm)
U_s	the average velocity in sink tube (mm)
$U_{\theta rp}$	Maximum swirl velocity in sink tube (mm/s)
B	coefficient depending on a velocity distribution in the sink tube
Γ	Kinematics viscosity (m^3 / s)
Θ	The swirl angel (degree)
Ρ	The density of fluid (kg / m^3)
Ω	The angular viscosity (rad/s)
Γ_0	Circulation retained by the flow prior to the entrance into sink tube (m^2 / s)
Γ_p	Core circulation (m^2 / s)