Vortex Rate Sensor with Modified Configuration

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Abstract**-- A gyroscope is essential equipment in all air vehicles. These vehicles sometime work in very challenging conditions like high temperature, noise and radiation. A vortex rate sensor as a fluidics gyroscope has been proposed to work in such conditions. This gyroscope has no moving parts with minimum manufacturing and maintenance cost. A modified vortex rate sensor has been design and manufactured of wood to study theoretically and experimentally the static performance of it. To carry out the experimental work; a rig has been designed and build. The experimental work was performed with four different air flow rate (50, 75, 100 and 125 L/min). The results show that there is a linear relation between the differential pressures taken of the sensor with its angular velocity and there is a good agreement between the theoretical and the experimental result.**

Index Term**-- Vortex rate sensor, Fluidics sensors, Angular vortex rate sensor and Fluidics gyro.**

I. INTRODUCTION

Fluidics is a science using fluid as a sensing media. Fluidics sensors are well known that they have no moving parts and can work under hard conditions, like high noise, high vibration radiation and high temperature. And it has no need for regular maintenance and it has minimum manufacturing coast. Vortex rate sensor is one of these instruments; it works instead of gyroscopes systems in rocket, aircraft and in all air vehicles. A typical vortex rate sensor is shown in fig. 1. A cylindrical chamber has a supply manifold surrounding it and between them there is a porous wall. In the absence of any disturbances, the flow enters radially and proceeds upwards and drained through the output sink tube shown in the chamber center. When a constant angular velocity is applied to the sensor, a tangential velocity component is introduced in to the vortex chamber, the resultant a flow comes out through the sink tube in a form of helix. In this helix flow, the angle of helix is proportional to the momentum imparted, which in turn will depend on the angular velocity applied before to sensor chamber. A two pickup tubes are inserted in the output sink tube, both of pickup tubes show the same pressure when the flow comes out undisturbed, when the chamber is disturbed, the flow comes out in a form of helix, the two pick up pressure tube show different pressure, one higher than the other depending on the direction of rotation. The pressure difference shown is proportional to the angle of helix and its direction. The direction of helix will depend on whether the body is rotated clockwise or counter clockwise, and the magnitude depends on angular rate. Such rate sensors have been very effectively used in rockets and space craft.

Many researchers worked theoretically and experimentally on vortex rate sensor, among these researchers are:

Organ H.D. [6], in 1965, the conventional type of vortex rate sensor with different porous media was used, he used two cylindrical screen members outer and inner, the screen of the inner porous media has smaller diameter of the outer.

Barrett Doyle [2], in 1966, vortex rate sensor with common geometry with different differential pressure pick off technique was made, he used an optical means for providing an output signal proportional to the sensor rotation.

Camarata ,F.J [3], In 1969, a twin vortex rate sensor was invented, each having its axis or center line coincident with the axis of the moving body to be sensed. The output pressure of each vortex is compared with that of the other and the differential of such output pressure provide a signal indicative of the rate and direction of the rotating body.

Sartkaya T. [10], In 1973, the performance of pneumatic vortex rate sensor was studied by using a series of vanes and viscous coupling instead of using porous coupling which is used in all other vortex rate sensors. A new pick off signal system used by the researcher comprised of two spherical elements. He found that there is a good agreement between the theoretical and experimental results.

Konami S., Hayashi J. and Tsukahara T. [5], in 1976, they studied theoretically and experimentally the dynamic and static characteristics of the vortex rate sensor. The experimental work includes changing the vortex chamber thickness and supply flow rate. They concluded that the total time delay of the vortex rate sensor is composed of time delay associated with the development of a stabilized tangential flow at the vortex chamber periphery plus the puro delay time associated with the fluid transport phenomena invented.

Norton P. [8], In 2006, a vortex rate sensor for measuring yaw rate or roll rate for an automotive vehicle was Invented, the sensor comprises a freely rotating internal disk and angular rate sensor responsive to the rotation of the internal disc relative to housing. In one embodiment, the internal disk presents an alternating magnetic field at its circumference. The rate and direction of rotation of the internal disk relative to its housing is determined by three magnetic field sensor. In another embodiment, electronic camera's measure the movement of the internal disk. Air surrounds the internal disk, brings the disk to gradual stop by its viscosity.

Al-Asadi A. M. and Kadhum W. G. [1], In 2012, a wooden vortex rate meter similar to that used by sarpkaya T,A was designed and manufactured to steady theoretically and experimentally the static performance of vortex rate sensor but they used a series of slices and porous media made of sponge was inserted in the inlet region of the cylindrical space ,the purpose of the porous media and slices were to ensure a uniform flow at the outside edge of the cylindrical space. From the result they found that the relation between the angular rotation of the sensor and differential pressure picked up by the sensor is linear. By the new sensor configuration in our work, we can have a uniformly distributed flow of air around the cylindrical space and there is a gradual change in flow direction if it is compared with other designs.

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II. SENSOR AND TESTING RIG DESCRIPTION

The sensor is made out of wood, its dimensions are (the diameter of the cylindrical space is 250mm, sink tube diameter is 8mm, pickoff hole diameter is 2mm, thickness of the metal vanes is 20mm and the height of the cylindrical space is 20mm), see fig. 2. It consists of three wooden parts, the base, the cover of the base and the wooden cone which is attached to the base and surrounded by a sheet metal cone ended with air coupling. Between the base and the cover, there is a cylindrical space. A (9) millimeter hole is drilled in the center of the cover part to fit the sink tube for a differential pressure measurement. By this new sensor configuration we can have a uniformly distributed flow of air around the cylindrical space and there a gradual change in flow direction. After that, the flow passing the vane which is used to direct the flow towards the chamber center to the sink tube. The pickoff tube used is made of copper, is passed across the sink tube as shown in fig. 3. The pickoff hole was positioned at 45° to the flow direction in order to obtain the optimum differential pressure readings. Fig. 4 show the test rig, it consist of the electrical driven compressor with capacity of 200 L and maximum pressure of 10 bar to supply the air used in the test rig as working media, regulator valve to fix the pressure of the flow going to the sensor, rotometer to measure the flow rate and a flow regulator valve, vortex rate sensor, pick off element and the differential manometer to measure the differential pressure. Plate 1 show the test rig built in the laboratory.

III. SENSOR MATHEMATICAL ANALYSIS

We can assume that the pickoff hole work like a Pitot tube because they read the stagnation pressure at that point. So Bernoulli's equation can be applied which states that the stagnation pressure equal static pressure plus dynamic pressure at that point. Because the pipe opened to the atmosphere static pressure equal to zero then the dynamic pressure of the flow can be equal to ($\frac{\rho V_S^2 \sin\alpha}{2}$) after we apply the following assumption:

1. The flow is inviscid.
2. Incompressible
3. Neglect body force
4. Steady state

The pickoff holes are located at equal distance - rh and + rh from the sink tube centerline at an angle equal to α to the sink tube and when the sensor in stationary under constant flow rate the pressure reading at the pickoff hole is equal

$P_1=P_2$ and $P_1=P_2=0.5\rho J^2 V_S^2 \sin^2\alpha$ ...(1)

For turbulent flow J=1.12 **[7]**.

When the sensor have an angular velocity equal ω spiral flow would be induced in the sink tube which lead to differential pressure across the pickoff holes equal to ΔP then ΔP in the differential pressure across the pickoff tube. 1&2

$P1=0.5\rho J^2 V_s^2 \sin^2\alpha_1$ ... (2)
$P2=0.5\rho J^2 V_s^2 \sin^2\alpha_2$ … (3)
$\Delta P=P_1-P_2$ … (4)
Substitute eq. 2 &3 into eq. 4
$\Delta P=0.5\rho J^2 V_s^2 \sin^2\Delta\alpha$ … (5)
Where $\Delta\alpha = \sin^2\alpha_1 - \sin^2\alpha_2$ ... (6)

The swirling angle, resulting from the tangential velocity of fluid relative to the tangential velocity of the pickoff hole is given by [3].

Then

$$\tan\Delta\alpha = \frac{V_{sw} - r_h\omega}{JV_s} \quad \text{... (7)}$$

$$\Delta\alpha = \frac{V_{sw}}{JV_s} \quad \text{… (8)}$$

Where V_{SW} is the maximum swirl velocity at radius r_h in the sink tube.

$$V_{sw} = \frac{K\omega D^2}{4r_h} \quad \text{… (9)}$$

Where the tangential velocity is maximum.

$K = \Gamma_c/\Gamma_i = 0.71$ **[7]**.

Substitute eq.9 in eq.8 and then in eq.5

$$\Delta P = 0.5\,\rho\omega JKV_S\left[\frac{D^2}{4r_h}\right] \quad \text{... (10)}$$

The maximum tangential velocity occurs at a radial distance ranging from $0.3r_s$ to $0.4r_s$ Where r_s the radius of sink tube.

Then $r_h = m.r_s$ where m is constant =0.376 [8].

Multiplying eq.10 by $\frac{Q}{Q}$ where $Q = \pi r_s^2 V_s$ Then eq. 10 becomes

$$\Delta P = 0.085\left(\frac{\rho\omega Q}{r_s}\right)\left(\frac{D}{r_s}\right)^2 \quad \text{… (11)}$$

Where ΔP is in N/m2

To read the differential pressure in mm of water

$$\Delta P = \rho_w g h \quad \text{... (12)}$$

$$h\,(m\ of\ water\,) = \frac{\Delta P}{\rho_w g} \quad \text{…(13)}$$

It is obvious from eq.10 that the differential pressure readings of the sensor is proportional to the angular velocity, flow rate and sensor cylindrical chamber diameter and it is inversely properties to r_s.

IV. TEST PROCEDURE

To carry out the experimental part of the work first we check all the component of the rig and prepare the rig by following the procedure bellow:

1. Turn on the compressor which is 200L capacity until the pressure reach 10 bar.
2. Open the flow regulator valve to specific position to control the flow rate.
3. Before applying any angular velocity to the sensor make sure that the manometer reading is zero.
4. Fix the flow rate of the air going to the sensor and apply different angular velocity.
5. In each angular velocity applied to the sensor we record the differential manometer reading in mm of water
6. We repeat the procedure many times to make sure of the reading
7. We apply the above procedure to four flow rate (50,75,100,125) L/min

V. RESULTS AND DISCUSSION

In this work a wooden vortex rate sensor with modified configuration has been designed and manufactured with the following dimension. The diameter of the cylindrical space is 250 mm, diameter of the sink tube is 8mm, pickup holes diameter is 2 mm. An experimental and theoretical work has been conducted to steady the static characteristic of the sensor; fig 5 shows the result of the experimental side of the work (i.e. the relation between the differential pressure read by the pickup holes and the sensor rotation in different flow rate). It is obvious from the figure that the relation is linear except of some queer points up to 90 deg/sec this was due to the fact that the total velocity vector in the vicinity of the pickup holes was not in the plan normal to the pickup cylinder ,the second reason is because the constricting effect of the pickup element which in turn altered the velocity profile and accelerate the flow ,the third reason the separation and vortex shading which created due to pick up cylinder presence. Fig. 6 show the static characteristics of the sensor theoretically for different flow rate starting from 50 L/min up to 125 L/min, it is obvious that the relation between the differential pressure and the sensor rotation is linear and the differential pressure increases as the angular velocity of the sensor increases also it obvious that the sensitivity of the sensor increases as the flow rate increases. Fig 7 shows a comparison between the theoretical and experimental results , a quick examination of the data shown by the figure we can say that the theoretical sensitivity of the sensor more than the experimental for the same flow rate but any way the experimental results show a good and promising results. Obviously from the results we can say that the cylindrical pickup points yields reasonable differential pressure output ,so the output remains linear up to angler velocity equal 90 deg/sec after this velocity the swirling flow in the sink tube un distributed uniformly the second reasons is that the pickoff tube has little deviation from the center line of the sink tube which not able to eliminate the flow separation and vortex shedding .between the theoretical and experimental results there is a deviation to calculate it we took the results when the flow rate is 75L/min and for 8 points. From the results it is shown that the standard error of estimate (S_{yx}= 0.520645), and the coefficient of determination (r^2= 0.99798). The linearity of the vortex rate sensor (i.e Δp versus ω) is also calculated from measuring the maximum input deviation to the maximum full scale input:

Non-Linearity=((max.input dev.)/(max.full scale input))* 100

The non-linearity of the sensor is 3%. From the experimental curve, it is found the regression factor is 0.9955, so we can say that the vortex rate sensor is linear to differential pressure Δp. resolution is the smallest measurement sensor can reliability indicates. The resolution of the sensor is about 5mm of water.

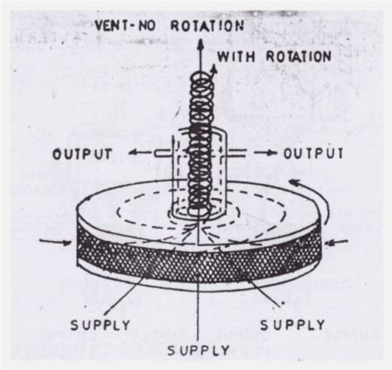

Fig. 1. Typical Vortex Rate Sensor [10]

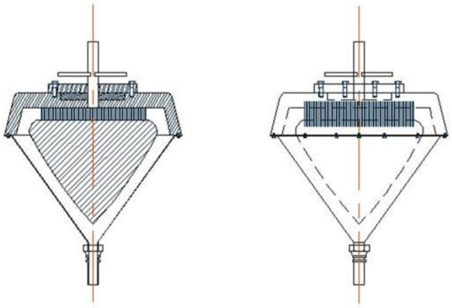

Fig. 2. Modified Vortex Rate Sensor

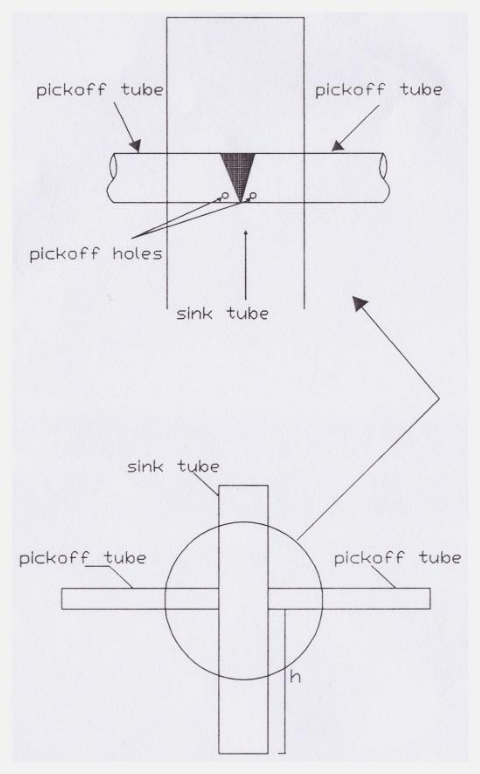

Fig. 3. Pickoff Element

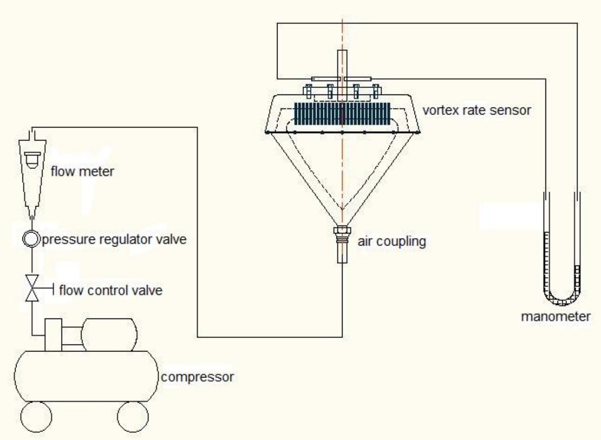

Fig. 4. Test rig and Instrumentation.

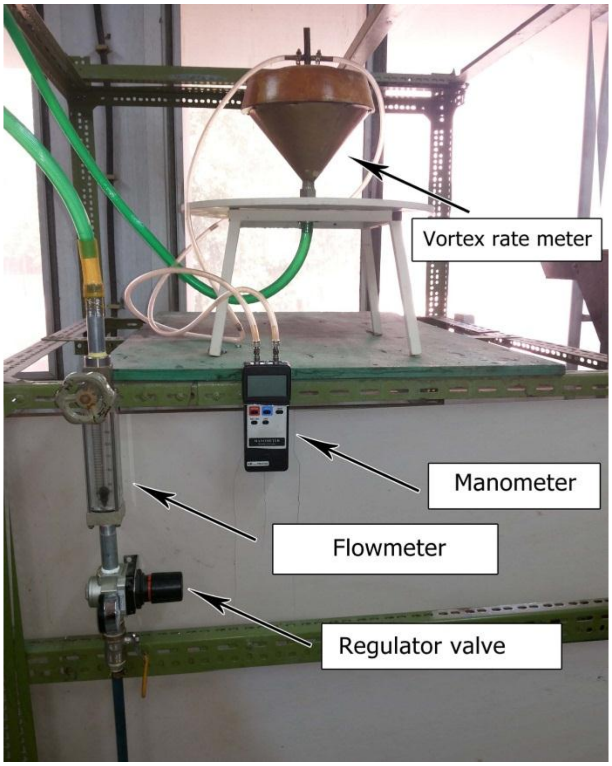

Plate 1. Test Rig

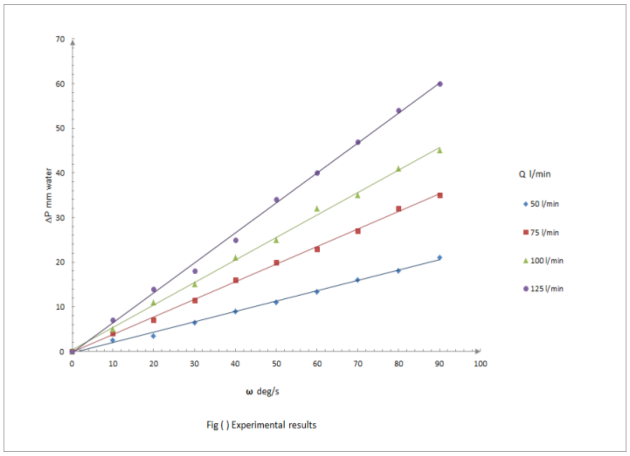

Fig. 5. Experimental results

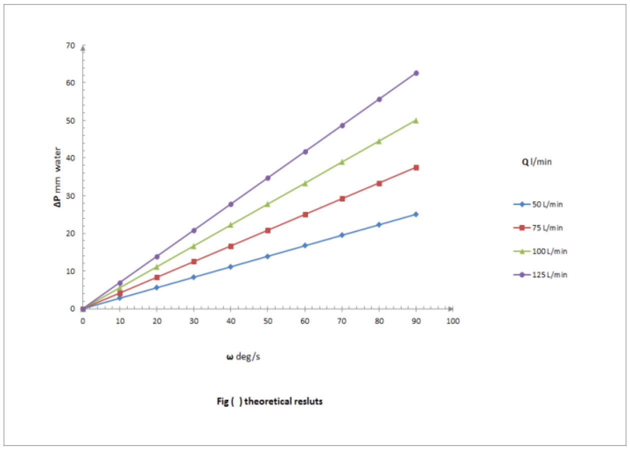

Fig. 6. Theoretical Results

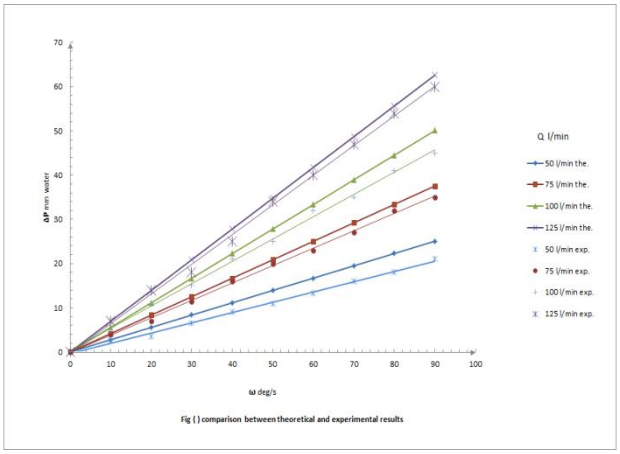

Fig. 7. Comparison Between Theoretical and Experimental Results

IV. CONCLUSIONS

The theoretical and experimental performance of the vortex rate sensor under consideration and the comparison between them are presented in figs(5,6 and 7),from the figures we can conclude the following.

1. The relation between the differential pressure read by the manometer and the sensor rotation is linear.
2. The sensitivity of the sensor is increased as the flow rate increased.
3. Because of the linearity property of the sensor it can be used instead of the gyroscopic system used by airplane and rocket because of gyroscopic system complexity and vortex rate sensor simplicity.

REFRENCESES

[1] AlAsadi A. A., Kadhum W. G. " Static Performance Characteristics of Vortex Rate Sensor", Journal of Engineering, University of Baghdad, PP 829-836, Volume 18 July, 2012.

[2] Barret Doyle, " Vortex Rate Sensor". U.S patent3,240,060 (Mar 1966)

[3] Camarata ,F.T. "Twin Vortex Angular Rate Sensor", U.S Patent 3,447,383, June 1966.

[4] Foster K., Parker G. A., "Fluidics Component and Circuits ", McGraw-Hill Company, 1970.

[5] Konami S., Hayashi J. and Tsukahara T., "The performance characteristic of a Vortex Rate Gyro", Bulletin of J.S.M.E, Vol. 19, No.132 (June 1976).

[6] Orgen H.D., "Vortex Rate Sensor",U.S Patent 3,203,237, Aug 1965.

[7] Pavlln C., "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.

[8] Peter N., "Angular Rate Sensor", U.S Patent 7,132,936 B1, Nov 2006.

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

[10] Sarpkaya T.,"A Pneumatic Vortex –Angular Rate Sensor-Analysis and Experiments", second IFAC symposium on fluidics, Vol.9, PP.29_34, pergamon press, 1973.

[11] Subir K., "An Introduction to Fluidics", OXFORD & IBH publishing company, New Delhi, 1984.

[12] Tatsaya C.I., Shoji K., Chiaki I., "On a Vortex Angle Rate Sensor", J.S.M.E, Vol.12, no.7, 1973.

[13] Wilton P.L., & Sbu W.G. "Flight Investigation of a Fluidics Auto Pilot System", National Aeronautics and Space Demonstration, D.C, July 1979.

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NOMENCLATURE

Symbols	Meaning
K	Viscous coefficient within sink tube
g	Gravitational acceleration (m/s^2)
P	pressure distribution for potential flow across the cylindrical space (m water)
D	Effective diameter of the vortex rate sensor (m)
r_h	The radial distance to the pick off hole (m)
r_s	Radius of the sink tube (m)
V_s	Average velocity in the sink tube (m/s)
V_{sw}	Maximum swirl velocity in sink tube (m/s)
J	Coefficient of the velocity distribution in sink tube
ν	Kinematic viscosity (m^2/s)
α	Swirl angle (degree)
ρ	Mass air density (kg/m^3)
ρ_w	Mass water density (kg/m^3)
ω	angular velocity (rad/s)
Q	volumetric flow rate (m^3/s)
Γi	circulation retained by the flow prior to entrance to the sink tube (m^2/s)
Γc	core circulation (m^2/s)