

FLUIDIC ANGULAR RATE SENSOR -

a replacement for rate gyroscopes ?

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A very simple fluidic angular rate sensor is described wherein angular rate information is obtained by sensing the deflection of a laminar jet flowing from a nozzle. Both the electrofluidic jet position sensor and no-rotating-parts fluidic pump, which are instrumental in yielding a low cost, long life, self-contained fluidic angular rate sensor, are discussed. The prime advantages of this rate sensor when compared with the conventional mechanical rate gyroscopes are its over-range capabilities, inherent long life, freedom from rotating parts, and extreme ruggedness.

As a result of APL's participation and encouragement, the Allegany Ballistics Laboratory (ABL), a Division of Hercules Incorporated, is developing a fluidic rate sensor. APL has participated in this development by defining requirements, testing early devices, and by direct financial support. The Fleet Systems Division at APL, having a continuing interest in gyro development, particularly in the areas of low cost and long life, has partially funded the development of the fluidic rate sensor for possible future application to shipboard systems. The inherent low frequency response fluidics had directed early attention toward shipboard applications since missile system applications generally required higher frequency response. Recently however, self-contained fluidic sensors have been developed in the standard miniature rate-gyro-size (1 in. diameter x 2 in. long) with a linear range to 1000 degrees per second having a dynamic capability to 50 Hz.

Description and Mechanization

The basic description of the sensor is contained in its name, "Fluidic Angular Rate Sensor." "Fluidic" is a term that has evolved in recent years to describe fluid systems where signals as well as power are transmitted by the fluid medium. Angular rate sensor means a device which, through its mechanization, yields an indicated output proportional to an input angular rate about a particular axis. In the fluidic angular rate sensors discussed here, the fluid medium is air, nominally at atmospheric pressure.

Before the technical details of operation and performance of the fluidic angular rate sensor are discussed, a simplified description of the device and its mechanization will be presented. Referring to the simplified sketch (Fig. 1), an air pump connected to a long, small-diameter tube creates a laminar air jet which, when undisturbed, flows along the centerline of the drift tube which houses

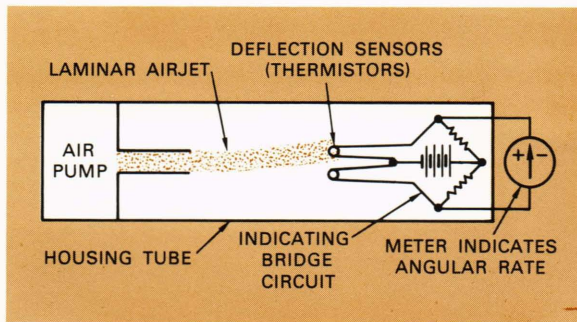


Fig. 1—Sketch of fluidic angular rate sensor.

the device. When the device is subjected to an angular rotation about an axis perpendicular to the centerline of the jet, the inertial properties of the air jet cause it to be deflected laterally. The magnitude and sense of the deflection are proportional to the magnitude and sense of the input angular rate. The two tiny thermistor deflection sensors are positioned symmetrically about the undisturbed air jet and separated a distance approximately equal to the jet nozzle diameter. The thermistors are electrically connected into a simple bridge circuit (as shown in the sketch) which provides enough current to cause self-heating of the two thermistors. In the undisturbed state the bridge is balanced and the meter indicates zero. When the air jet is deflected away from its normal centerline position, the velocity of the air flowing by one thermistor (toward which the jet is deflected) is greater than the velocity of air flowing by the opposite thermistor. This causes an unbalance in the cooling of the two thermistors. Since the thermistor resistance increases with decreasing temperature, the electronic bridge becomes unbalanced; this unbalance is indicated by a positive deflection of the meter. When the air jet is deflected in the opposite direction by a negative input angular rate, the other thermistor is cooled, thus unbalancing the bridge in the opposite sense. This causes the meter to indicate a negative value. Thus the device yields an indicated output, the magnitude and sense of which are proportional to the input angular rate about a particular axis.

JET DEFLECTION MECHANISM—Referring to Fig. 2, which shows a schematic diagram of the fluidic angular rate sensor, a free jet having a mean velocity V_j emerges from a nozzle and is deflected from the nozzle centerline by an amount d due to rotation of the system.

If the rotation is at a constant angular rate ω in the plane of the jet position sensors, the tangential velocity of the nozzle will have a value of $V_n = X\omega$, the resulting tangential velocity of the jet position sensors will be $V_s = (X + L)\omega$, and their difference

will be $V_s - V_n = (X + L)\omega - X\omega = L\omega$. Let t be the time for an increment of fluid to travel from the nozzle to the receiver ports. Then the deflection of the fluid beam is:

$$d = (V_s - V_n) t = (L\omega) t = Lt \cdot \omega = \frac{L^2}{V_j} \omega.$$

By letting L and V_j be constant, the deflection of the jet from the jet position sensor will be proportional to ω .

Naturally the above calculation holds only for small deflections. As will be shown later, the deflections in a practical device are very small compared to the length of the fluid beam and, therefore, the errors involved in the linear approximation are negligible.

It should be clear by inspection that the device is not sensitive to a constant velocity in any direction. Jet deflection is also not affected by a constant acceleration in any direction. The jet is completely submerged within the housing (drift tube) so that acceleration identically affects each element of the jet and the air in this space. Acceleration can, however, produce a constant density gradient in the housing. The change in the density may cause some second or higher order effects, but these effects should be very small.

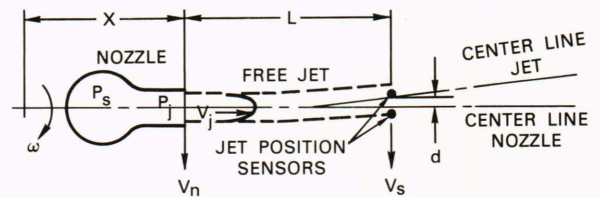


Fig. 2—Schematic diagram of fluidic angular rate sensor.

JET POSITION DETECTION—Detection of the magnitude and direction of deflection of the fluid beam is necessary if a usable output signal is to be generated which indicates the input angular rate. Because of the fluid entrainment property of a laminar submerged jet, the velocity distribution takes on approximately the parabolic shape shown in Fig. 3. Since the velocity varies across the jet beam, the dynamic pressure resulting from the velocity distribution also varies across the jet beam, as do many other properties of the jet. Any one of these properties could be used to determine the deflection of the jet. However, in the present designs, the fluid beam position is detected by the use of two thermistor beads located in the flow as shown in Fig. 3. Two 0.01-in.-diameter thermistor beads are mounted in a drift tube downstream from the nozzle and electrically connected into a

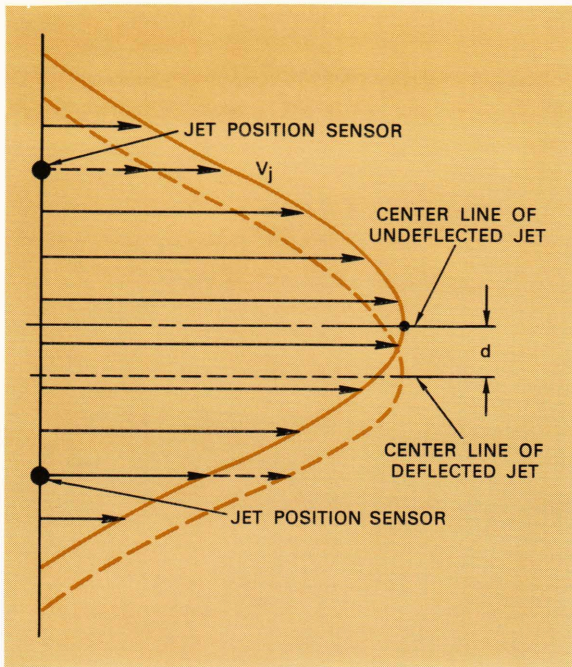


Fig. 3—Velocity profile at jet position sensor location.

balanced bridge configuration. The bridge is excited with a DC voltage and adjusted to allow enough current to flow to cause the thermistor beads to be self-heated to a temperature just above the ambient fluid temperature. As a result, heat is transferred to the ambient fluid as it flows past the tiny beads. Since the velocity distribution varies across the jet, the rate of cooling of the self-heated beads will vary with their positions in the jet. If the matched beads are both located at positions in the jet so that the velocity across each is equal, the cooling of each bead will be the same, their resistances will be equal, and the bridge will be balanced. With the beads properly spaced and symmetrically placed in a jet having the correct velocity profile, the electrical output, which results from differential cooling that occurs as the jet is deflected, can be made proportional to jet deflection over a wide range of values. The \pm sense of the input angular rate is contained in the \pm output voltage.

Some of the physical characteristics of the jet, nozzle, and deflection are as follows:

Nozzle diameter, $D = 0.125$ in.

Jet mean velocity, $V_j = 100$ in./sec

Distance to jet position sensors, $L = 1$ in.

Reynolds Number (Re) at nozzle $= \frac{DV_j\rho}{\mu} \cong 350$, where ρ and μ are density and viscosity of air at standard conditions. The flow is laminar if $Re < 1000$.

The time for a sample fluid to travel from the nozzle to the jet position sensor is: $t = L/V_j = 0.01$ sec.

Resulting deflection values for input angular rates as computed from the equation

$$d = \frac{L^2}{V_j} \cdot \omega = \frac{(1)^2}{57.3 (100)} \cdot \omega$$

are $d = 3.5 \times 10^{-3}$ in. at $\omega = 20^\circ/\text{sec}$ and $d = 1.75 \times 10^{-6}$ in. at $\omega = 0.01^\circ/\text{sec}$.

These deflections are certainly small compared to the length of the fluid beam L , and hence the linear approximation equation for deflection holds and second-order effects are very small.

This fluidic angular rate sensor could be designed as a fluoric angular rate sensor (that is an all-fluid sensor) by locating the two input control ports of a very sensitive fluidic amplifier at the respective locations designated as jet deflection detectors (in Fig. 3) in such a manner so as to be most sensitive to the dynamic pressure of the jet. The output of such a device would be a fluid

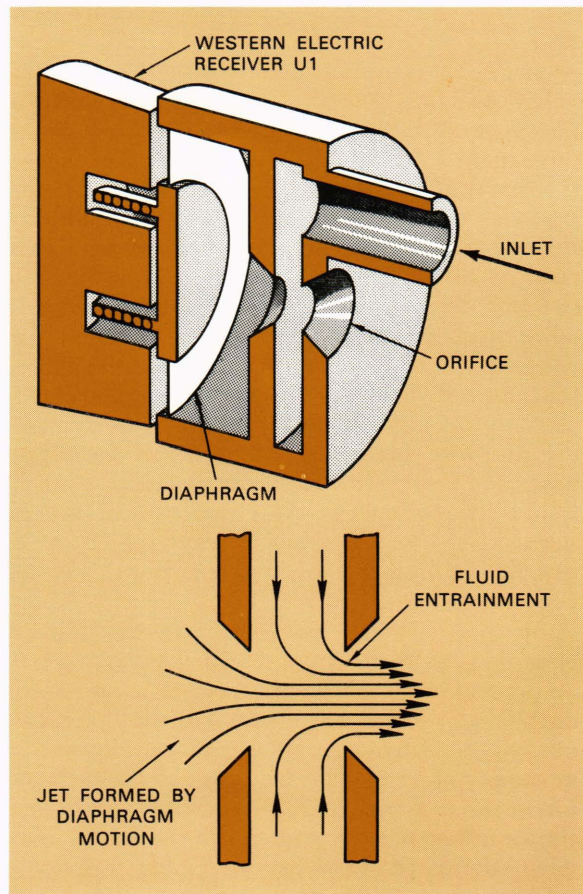


Fig. 4—Fluid pump cross section and pumping mechanism.

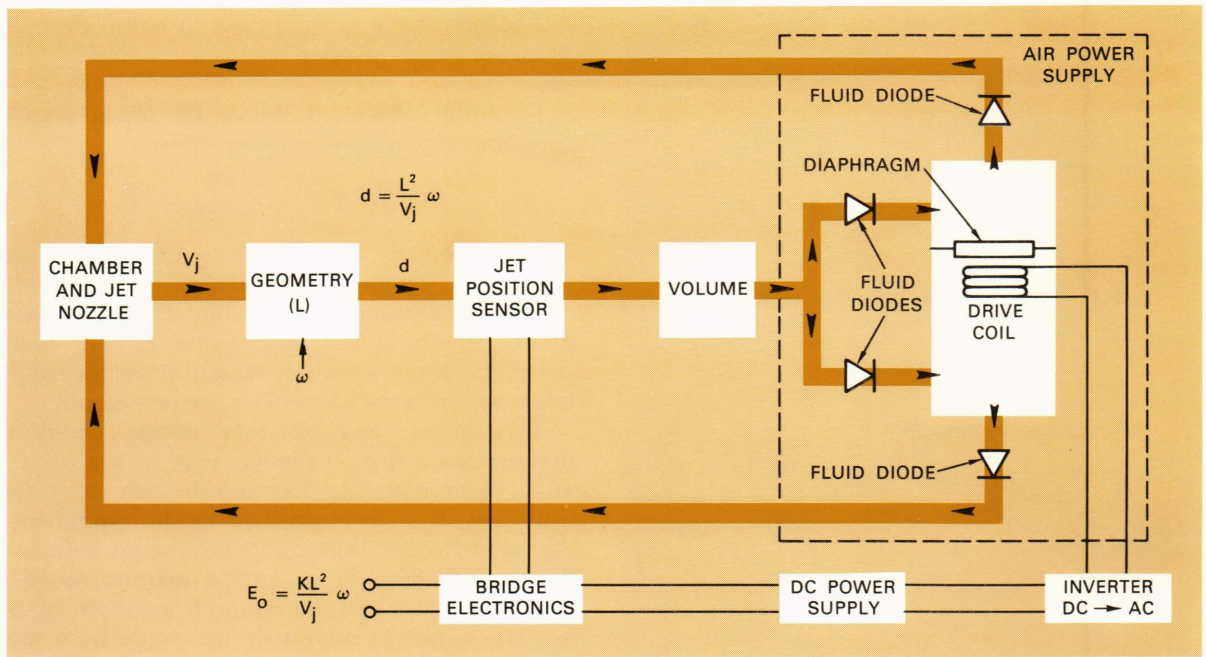


Fig. 5—Functional block diagram of sensor, including air power supply.

pressure that is proportional to input angular rate.

ELECTRONICS—A very simple passive electronic thermistor bridge may be used to get a usable output signal. However the thermistor beads have a thermal time constant in the range of ~ 0.15 to 2 seconds, which limits the dynamic capabilities of the rate sensor. The thermal time constant can be reduced to ~ 0.001 second by connecting the thermistors into an active electronic bridge in which the thermistors are held at a constant temperature. To further improve the dynamic characteristics, hot-wire anemometry techniques can be used; in this method the thermistors are replaced by tiny wire filaments. All of these techniques have been tested with excellent results.

AIR POWER SUPPLY—Rate sensors, like all other inertial sensors, are almost always subject to the system requirements of low cost, long life, and ruggedness.

The first of these, low cost, requires simplicity of design, while the second and third require the minimization of moving parts, etc. The laminar jet angular rate sensor has eliminated the large spinning wheel used in the rate gyroscope. However an air supply must be provided. This could have been a hose from a regulated air pressure source or a simple fan or blower mounted in the sensor itself. ABL eliminated these by developing a long-life, no-rotating-parts air pump as shown in Fig. 4. Early models of the air power supply utilized a Western Electric Type U1 earphone to move air

back and forth through special orifice plates to produce a very low pressure pump. More recently developed sensors use a piezoelectric crystal as the driver element.

The pump consists of two parallel orifice plates with a hole in each plate as illustrated in Fig. 4. The holes are opposite each other, and the hole diameter is approximately equal to the distance

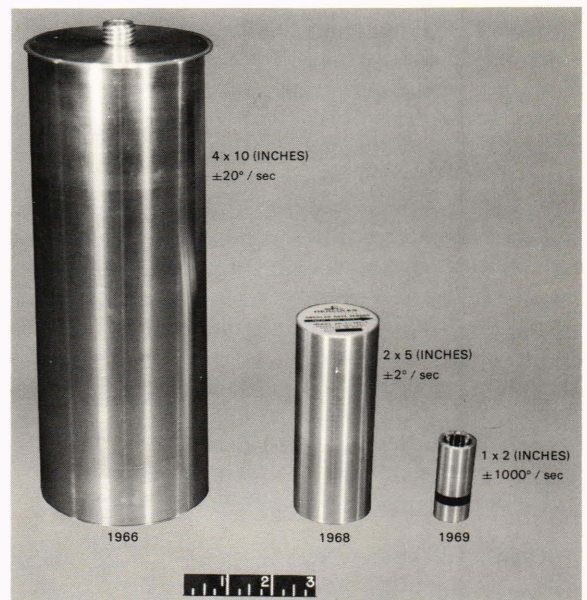


Fig. 6—Evolution of the fluidic angular rate sensor.

between the plates. As the diaphragm is displaced, a jet is formed by the orifice in the upstream plate. The jet diameter contracts in the usual manner as it moves across the gap toward the hole in the downstream plate. As the jet is crossing the gap, fluid between the plates is entrained by the jet and exhausted through the downstream hole. As the motion of the diaphragm reverses, a jet is formed in the opposite direction. Because of the symmetry of the orifices, fluid from between the plates is again exhausted through the downstream orifice. If the space between the plates is connected to a tube, fluid will be drawn through this tube and exhausted through the orifices as the diaphragm is caused to oscillate back and forth. The device, therefore, is a pump and will provide either pressure or suction.

Figure 5 is a functional block diagram of the ABL fluidic angular rate sensor showing how the fluid flows through the pump and the sensor. No attempt is made here to define transfer functions of each block. The jet nozzle and cavities throughout the sensor act as RC type filters to smooth the rectified pump flow to a clean noise-free flow at the jet position sensor location.

The rate sensor has been reduced to a package 1 in. in diameter and 2 in. long for some applications (see Fig. 6). Figure 7 shows actual photographs of one of the ABL experimental fluidic angular rate sensors as delivered to APL as part of a development contract. Figure 8 is an artist's illustration of the fluidic angular rate sensor showing the fluid flow as well as showing the location of each sub-unit of the sensor (e.g., pump, jet position sensor, nozzle, etc.). Note that this fluidic angular rate sensor has a DC output and requires only a DC power supply.

Performance

Performance testing has been conducted on first, second, and third generation fluidic angular rate sensors at APL and on the fourth generation units at ABL. Table I summarizes the results of these tests to show performance and progress. In general the units have a nonlinearity less than 0.2%, a dynamic range in excess of 2000 to 1, and a frequency response capability up to at least 300 rad/sec.

Generation 1 and 2 sensors were not designed for any specific application but rather as experimental devices. The third generation sensors have been delivered to APL for evaluation as an angular rate sensor for input to a target engageability computer. The fourth generation sensor is a first attempt at missile-type rate sensors. The 1-in.-diameter by 2-in.-long self-contained unit has a linear range to $\pm 1000^\circ/\text{sec}$ with a frequency

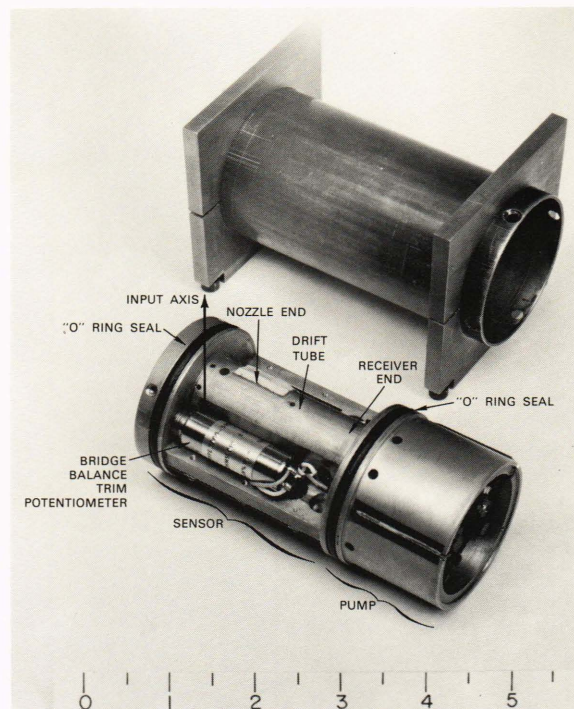


Fig. 7—Sensor with cover removed to show the relative location and size of all major parts.

response in excess of 300 rad/sec. The self-contained power supply uses a small piezoelectric crystal for the pump. Power requirements for the sensors are typically less than 1.5 watts.

The fluidic angular sensor transfer function is basically a transport delay and a first-order lag. The transport delay is caused by the time required

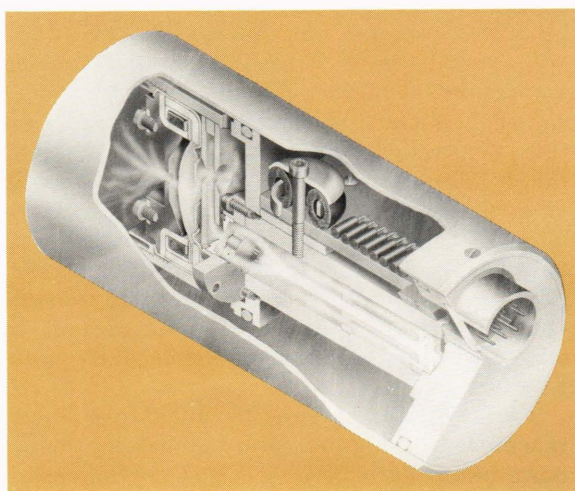


Fig. 8—Artist's concept of the second generation fluidic angular rate sensor.

TABLE I
SUMMARY OF PERFORMANCE PARAMETERS OF THE ABL FLUIDIC ANGULAR RATE SENSOR

<i>Performance Parameter</i>	<i>1966 First Generation</i>	<i>1967 Second Generation</i>	<i>1968 Third Generation</i>	<i>1969 Fourth Generation</i>
Range	± 20°/sec	± 20°/sec	± 2°/sec	± 1000°/sec
Nonlinearity	1%	0.2%	0.22%	0.5%
Bias Stability	—	0.001°/sec/day	—	—
Frequency Response	8 rad/sec	22 rad/sec	1 rad/sec	300 rad/sec
Resolution	<0.01°/sec	<0.01°/sec	0.002°/sec	0.3°/sec
Noise (at 0 input)	0.05%	0.05%	0.1%	0.3%
Size	Lunchbox	2-1/4 in. dia. x 4.75 in. long	2 in. dia. x 5 in. long	1 in. dia. x 2 in. long
Acceleration Sensitivity	5%/g	0.48%/g	1.5%/g	0.1%/g
Temp. Sensitivity				
Bias	—	0.07%/°F	0.12%/°F	0.05%/°F
Scale Factor	—	0.4%/°F	0.15%/°F	0.06%/°F
Voltage Sensitivity				
Bias	—	3.75%/V-DC	0.1%/V-DC	—
Scale Factor	—	14.3%/V-DC	0.25%/V-DC	—
Life	—	>16,000 hr (Units have been operating con- tinuously in ex- cess of 2 years)	—	—

(NOTE: All %'s are related to full scale values.)

for a slug of fluid to traverse the distance from the nozzle to the pick-off. The first-order lag is due to the thermal time constant of the thermistor beads. When a constant power bridge is used to improve the frequency response the lag appears at a higher frequency and a higher frequency second-order lag appears in the transfer function.

Table I gives a chronological listing for comparison of the performance parameters of all the fluidic angular rate sensors developed. One immediately sees the vast improvements in most areas and the areas where further improvements are desired. The bias stability (null wander) is caused by change of pick-off characteristics with time. Convective acceleration effects in the area of the jet position sensors are responsible for acceleration sensitivity. Imperfect matching of the two pick-off elements causes temperature sensitivities. Parameter stability (drift) and convective acceleration sensitivity have been reduced to tolerable levels for applications being considered, but remain the major areas of concern for future development.

Two of the early experimental fluidic angular rate sensors having the self-contained, no-rotating-parts pump have been operated continuously at APL for approximately two years (a total of 17,000 hours each) to determine life and stability characteristics. ABL has a similar unit that has oper-

ated for the same length of time. This is a total of 51,000 operating hours on the three sensors without any failure. The output wander for zero input rate has been monitored during the life testing. The rate of the "zero" drift has decreased from 0.043°/sec/day to 0.001°/sec/day. This indicates that the sensors get better with age, as was expected. The fluidic angular rate sensor therefore has all the advantages of fluidic elements, i.e., low cost, long life, and ruggedness.

The jet fluidic angular rate sensor is capable of exceptionally high over-ranging without any degradation of performance thereafter. If you highly over-range a gyroscope, you either destroy it completely or permanently change its performance parameters. The usual procedure using rate gyroscopes for such an application is to specify the highest expected rate and then suffer poor performance when operating in the low rate range because of the dynamic range limitation of the sensor.

Before comparing the merits of the jet fluidic angular rate sensor with those of another fluidic angular rate sensor—the vortex type—a brief explanation of the vortex type must be given. The vortex type fluidic angular rate sensor, utilizes a two-dimensional radial sink flow created by fluid flowing from a porous wall into a centrally located sink. This becomes a spiral sink flow when the

system is subjected to a rotation about the sink axis. Case rotation about this axis imparts a tangential component (relative to fixed coordinates) to the radially flowing fluid. Since angular momentum is conserved, a free vortex is generated, increasing the angular velocity of the fluid and resulting in an appreciable value at the sink relative to that at the wall. Tangential pitot tubes located near the center of rotation sense the dynamic pressure caused by the increase in tangential velocity of the fluid over the tangential velocity of the case. Both the sense and the magnitude of the input angular rate are contained in the pressure measurement.

In making a comparison between these two types of fluidic angular rate sensor the following conclusions are apparent. The jet unit has the advantage of simplicity, smaller size, smaller flow, smaller power requirements, and a much higher signal-to-noise ratio. The vortex type rate sensor must have a very high volume rate of flow to reduce

the transport delay time. The result of this is turbulence which introduces noise into the receiver area. The jet fluidic angular rate sensor operates at a low Reynolds Number (<500) which is well within the requirement for laminar flow. The vortex type rate sensor must have a large diameter since gain is proportional to diameter and it also requires a precision machining effort. The vortex type rate sensor has gone through approximately nine years of extensive development both by industry and by government as a rate sensor that is useful in fluidic systems. However, its limited dynamic range, high power requirement, and large size have limited its use to the all-fluid systems.

Development of the jet fluidic angular rate sensor continues in both theoretical and experimental areas to establish the performance capabilities and limitations of the basic sensor. It is expected that the sensor will find its way into shipboard systems and other applications where frequency response does not limit its usefulness.

ADDRESSES

Principal recent addresses made by APL staff members
to groups and organizations outside the Laboratory.

The following four addresses were given at the 1968 Fall Meeting of the *American Physical Society*, Miami Beach, Florida, November 25-27, 1968:

- R. Turner and T. O. Poehler, "Far-Infrared Laser Diagnostics of Transient Plasma;"
- W. R. Powell, "Spectroscopic Measurement of Electron Concentration;"
- H. M. Stainer, "Some Consequences of Rotation in a Model Theta Pinch;"
- C. S. Leffel, Jr., "Ion Analysis of a Theta-Pinch Gun."

R. W. Cole, "Responsibilities, Activities, and Procedures of the Satellite Reliability Group at APL," *Baltimore Chapter, IEEE Reliability Group*, Baltimore, January 27, 1969.

D. D. Zimmerman and R. E. Hicks, "Preparation of Substrates with Bumps for Face-Down Bonding of Hybrid Components," *National Electronics Packaging Conference*, Anaheim, California, February 11-13, 1969.

M. H. Friedman, "Free Swelling of Biological Tissue. The Corneal Stroma," *American Institute of Chemical Engineers, 64th Annual Meeting*, New Orleans, Louisiana, March 17-20, 1969.

W. H. Avery, "Aerial Car Transit System," *New York University Seminar*, March 21, 1969.

V. O'Brien, "Large Circulating Drops in the Gravity Field," *International Union of Applied and Theoretical Mechanics, Symposium on Flow of Fluid-Solid Mixtures*, University of Cambridge, Cambridge, England, March 23-29, 1969.

The following three addresses were given at the *American Physical Society*, Philadelphia, March 24-27, 1969:

- F. J. Adrian, E. L. Cochran, and V. A. Bowers, "ESR Spectrum and Structure of HNO_2^- in KCl ;"
- F. J. Adrian, E. L. Cochran, and V. A. Bowers, "CN Stretching Vibration in HCN ;"
- J. Bohandy, J. C. Murphy, and A. N. Jette (APL) and D. O'Shea and C. M. Wilson (The Johns Hopkins University), "Raman Scattering in X-irradiated KCl-Ag Crystals."

L. Monchick, "Calculation of Ortho-Para Hydrogen Scattering Cross Sections," *The Johns Hopkins University, Department of Chemistry Colloquium*, Baltimore, March 25, 1969.

R. A. Dickman, "The Use of Functional Job Analysis as an Aid to Personnel," *American Personnel Guidance Association*, Las Vegas, Nevada, April 1, 1969.

A. A. Westenberg, "Atom-Molecule Kinetics Using ESR Detection," *Interagency Chemical Rocket Propulsion Group*, Cleveland, April 10, 1969.

W. E. Radford and R. L. Hickerson, "Measurement of Earth Magnetic Field Oscillations at Synchronous Satellite Altitudes," *1969 International Conference on Magnetism (INTERMAG)*, Amsterdam, The Netherlands, April 15-18, 1969.

K. Moorjani, "Elemental Amorphous Semiconductors," *Physics Department, University of Maryland*, College Park, April 17, 1969.

E. Maumenee, L. V. M. Hyvarinen, and T. George (The Johns Hopkins University), and J. T. Massey and B. F. Hochheimer (APL), "Fundus Camera for Retinal Fluorescence Cinematography," *Bascom Palmer Eye Institute, Department of Ophthalmology, University of Miami*, Miami, Florida, April 20-23, 1969.