approaches only, is the longitudinal spread between the two crossings of θ_f by the vehicle ground track. Both are functions of i and initial altitude. Hence, for small maneuvering rectangles, these orbital parameters should be chosen carefully in order to obtain the lowest maximum delay times.

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Attitude Sensor for Vehicle Orientation in Space Flight

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ONE of the most vitally essential operations in manned space flight has been the precise alignment of the vehicle with respect to the orbit and the earth before igniting the retrorockets, and later, the precise realignment of the vehicle before re-entry into the earth's atmosphere. The only instrument system that has been available for these alignments relies upon sensitive precision gyroscopes combined with electronic and timing equipment for calculating the required alignment of the gyroscopes relative to the vehicle. However, in long, sustained flights, any gyroscope has a finite amount of drift that cannot be eliminated. Therefore, it is desirable to have a backup system that operates on an entirely different principle.

An attitude sensing system based on two pairs of ion probes has been developed and tested at North Carolina State in work that has been performed jointly with the Aerospace Division of The Boeing Company in Seattle. At altitudes above 300 kft, the earth's atmosphere is so rarefied that pressure gages cannot measure its density, but the density of the ionized material is more than sufficient to operate the attitude sensor reliably. By comparing the ion currents to the probes, the instrument directly measures the angle between the axis of the vehicle and the direction of motion without any need to know what the previous motion of the vehicle has been or should have been. Since it has no moving parts and has very simple electronics, the durability of this attitude sensor can be expected to be even higher than that of any inertial guidance system.

The two probes of each pair are mounted at an angle relative to each other (Fig. 1). If the probes are moving through an ionized medium, the number of ions that enter each probe will depend on the angle that the probe axis makes with the direction of motion. In a simplified theory, where we assume that the ions have negligible thermal speed

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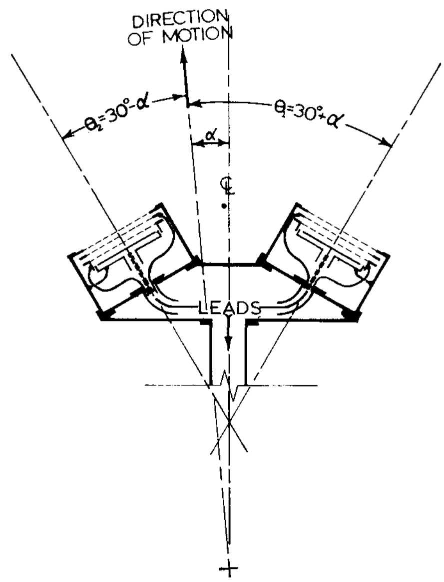

Fig. 1 Angles between velocity vector and ion probes in an attitude sensor.

when compared to the vehicle velocity u, the current i that will reach the collector in one of the probes is

$$i = neuA \cos\theta$$

where n = ion density, e = ion charge (assumed to be +1 electron charge), A = probe area, and θ = angle between the direction of motion and the normal to the grids in that probe.

In the figure, $\theta_1 = 30° - \alpha$ and $\theta_2 = 30° + \alpha$ so the ratio of the currents i_1 and i_2 picked up by probes one and two will be

$$R = i_1/i_2 = \cos(30° - \alpha)/\cos(30° + \alpha)$$

A simple method for finding R electronically is to feed the current from each of the probes into a logarithmic amplifier, so that $V_1 = K \log i_1$, and $V_2 = K \log i_2$, where V_1 and V_2 are the voltage outputs from the two amplifiers. Then the difference between the voltages is:

$$V_1 - V_2 = K[\log i_1 - \log i_2] = K \log(i_1/i_2) = K \log R$$

This voltage difference can be amplified by a transistorized difference amplifier and used to drive a display meter. Using this method, an indication of orientation to ±2° accuracy has been obtained by using simple electronics already developed.

An attitude sensor using ion probes that are mostly hollow would, of course, allow air to pass through, and hence, when used on a re-entering vehicle, should operate properly down to lower altitudes than would the above solid-plate type of probes. This kind of ion probe (Fig. 2) consists of a cylindrical outer shell, six control grids made of 0.001-in. knitted tungsten wire, a longitudinal diaphragm running part of the way down the cylinder, and two metal half cylinders inside the shell. The insulation shown may be either Kel-F or Teflon. All elements except grids one and six are insulated from the probe shell. These two grids are grounded to the shell to prevent any electric fields due to potentials inside the probe from extending into the medium outside the probe volume. Thus, the potentials inside the probe do not affect the motion of the charged particles around the probe.

The second grid is the ion-retarding grid. It may be used in one of two different ways, depending on the type of electronic instrumentation used. If a d.c. amplifier is used to read the ion current passing into the probe, the retarding grid is kept at 0 v allowing a steady ion current to flow. If an a.c. amplifier is used, the grid may be commutated between 0 and +20 v at a low frequency, thus producing an ion current alternating from a maximum value to zero. In our calibrations, the d.c. mode was used because of the simplicity of the amplifier required and the ease of calibration of the amplifier in the laboratory.

The third and fourth grids, called the probe screens, are held at −20 v to repel all electrons that enter the probe. Thus, the only particles that can enter the ion collection region of the probe are positive ions and neutral atoms or molecules. The probe screen grids also prevent any photo or secondary electrons emitted from the half cylinders or diaphragm from escaping and falsifying the ion current reading.

When the ions pass into the region between the half cylinders and the diaphragm, they are accelerated toward the diaphragm by a −13.5-v potential called the sweep voltage, which is applied between the diaphragm and the half cylinders. The diaphragm is connected to the negative side of a small 13.5-v battery, the positive side of which is connected to the half cylinders and to the input of the electronic instrumentation. In this way, any photo-electrons or secondary emission electrons that leave the diaphragm and are collected by the half cylinders do not change the current to the amplifier and falsify the reading, since the electron current only flows in the closed circuit containing the battery. The amplifier receives only the current due to positive ions collected.

The fifth grid is held at +20 v. It prevents any ions from entering from the rear of the probe if the vehicle is turned around. It also reflects high-energy ions that entered the front of the probe but were not pulled to the diaphragm on the first pass; these ions travel back through the probe and are attracted once again toward the diaphragm. This ion repulsion grid serves to make the collection of ions complete while using a sweep voltage of only 13.5 v.

The double ion probe consists of two single ion probes mounted at an angle relative to each other on a common support. In our calibrations, the angle between the probes was 60°. The wires that controlled the grid potentials in the probes were joined together in the truncated triangle joining the probes so there were only three control wires going from the probe system: one wire for the retarding grids, one wire for the probe screen grids (of which there were two in each probe), one wire for the ion repulsion grids. There were two leads from the ion collection region of each probe: one lead from the diaphragm, one lead from the split cylinder. Thus, there were seven leads from the double probe. The three control leads were comparatively low impedence leads, but the four leads from the ion collection regions were, of course, very high impedence and had to be well shielded.

The probe pair was tested in a vacuum chamber that could closely duplicate the actual conditions during orbit and re-entry. The chamber (Fig. 3) was made of a bronze bucket 9 in. high and 14 in. in diam, a glass cylinder 18 in. high, and a metal plate on top with two pressure gages and an ion source that beamed a stream of positive ions downward toward the probe. The chamber was pumped to an ultimate pressure of about 5×10^{-6} torr. During operation, a gas, usually hydrogen, was bled into the chamber through a copper tube to maintain the pressure between 2×10^{-5} and 8×10^{-5} torr, corresponding to an altitude of about 100 miles. The use of hydrogen in the chamber does not mean that the data taken is only representative of hydrogen, because the response of the probe is dependent only on the energy of the incident ions. Therefore, a 10.5-ev hydrogen ion would be equivalent to an oxygen ion as seen by a vehicle traveling at orbiting speed. The glass cylinder had a wall thickness of approximately 0.25 in. and was coated on the inside with a coating that was optically transparent but was electrically conducting.

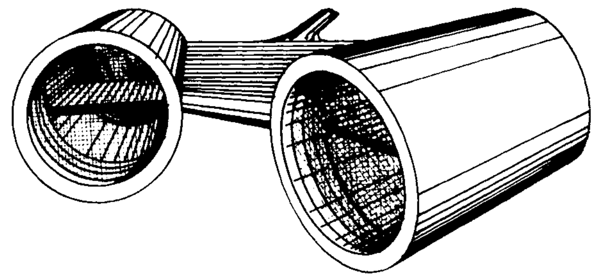

Fig. 2 A pair of ion probes used in an attitude sensor.

Figure 3 shows the electrode arrangement in the ion source. Electrons from the 5-mil tungsten filament held at −20 v from ground are accelerated downward through the cage, 1, which is held at about +8 v from ground. Ions formed in the cage are drawn downward by a +20-v potential on the "drawing out" grid, 2. Electrons from the filament are turned back by a negative potential of about −35 v applied to the "electron repulsion" grid doublet, 3. Ions pass downward through this grid with a spread in energy corresponding to the spread in energy of the various positions in the cage and below it from which ions can be accelerated after being produced by ionization of the gas in the ion source. If the potential on the lower grid doublet, 4, is about 5 v more negative than the cage, the distribution in energy of the ions which passes down through this doublet is nearly a Maxwellian distribution. The lowest single grid, 5, is grounded to the test chamber and is used in order to avoid excessive spreading of the ion beam away from the axis due to electric fields produced by potentials applied to the lower grid doublet.

Using this source, an ion spectrum may be projected towards the attitude sensor probe pair with any average energy between 1 and 12 ev or more, depending on the cage potential. Any desired "thermal" energy spread can be obtained by adjusting the potential on the lower grid doublet, 5.

During orbital and re-entry conditions, the maximum energy of any ion encountered should not be greater than around 14 ev. For example, the kinetic energy of NO^+ moving relative to the vehicle at a velocity of 8×10^3 m/sec is about 10.5 ev. If the vehicle were at a potential of about

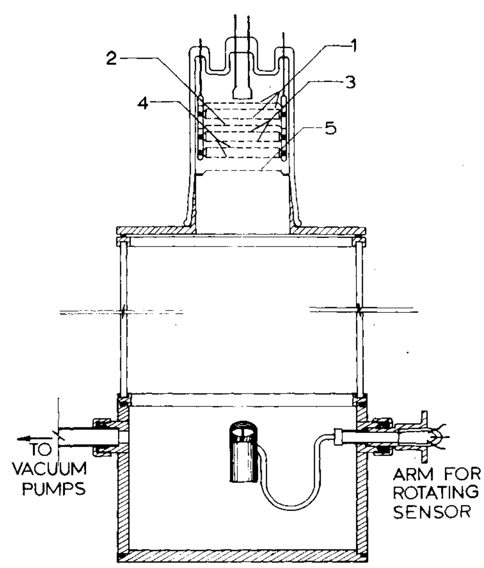

Fig. 3 Test chamber for calibrating the attitude sensor under simulated flight conditions. Ion source is shown enlarged by a factor of two as compared with rest of the figure.

-2v, the kinetic energy of the ion at the probe would then be about 12.5 ev.

It was found that the minimum potential on a single grid necessary to repel all 14 ev particles was about 18 v. The probe screens were run at -20 v, the ion repulsion grid at $+20$ v.

The fidelity with which the difference in logarithms of the probe currents followed the idealized expression derived previously:

$$V_1 - V_2 = K \log[\cos(30° - \alpha)/\cos(30° + \alpha)]$$

was thoroughly tested for all values of α up to 45°. It was found that the simple formula was followed with an error of less than 2° up to values of $\alpha = 30°$.

The plane of the axes of the two probes in the pair was then rotated 30° away from the vertical, and the fidelity was again tested. It was found that the error was less than 2° for angles up to 25°.

These tests have shown that an attitude sensor consisting of two ion probe pairs in planes at right angles can be relied upon to give both angle of attack and angle of yaw accurately up to 25° for either or both to within less than 2° error. It is estimated that, with refinements that are evident now, the accuracy can readily be improved to give the angles to less than 0.5° error.

Determination of Probability of Success of Mission Given the Component Probabilities

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THIS note presents a simple model for the estimation of success of well-defined systems of general complexity as a function of time and based on the probabilities given for the components of the system. The technique assumes that the components (blocks, subsystems, etc.) are clearly identified and that the connections among the components are precisely specified and fixed for each phase of system operations. If the connections are not well defined, the system is clearly not sufficiently designed and not analyzable. For each such organization of components, a Boolean equation is formulated.

It is also assumed that the components have two states, either fail or not fail. This assumption is made only for convenience. Three states, or, in general, n states might have been assumed, but this would only have increased the computational complexity without offering a conceptual change.

Finally, it is assumed that the probability of fail of each component is given as a function of time over the whole interval of operation of the system. If the likelihood of failure of one component depends on that of another, a unique functional relation still obtains for each component.

With these assumptions, the computational procedure is as follows: 1) formulate the Boolean expression for the organization of components for each phase of the mission; 2) evaluate each of these Boolean functions for all of the two-state variables, using standard logic table methods; 3) construct the probability of success (or fail) functions for each row entry in the table for each of the Boolean, or phase, functions; 4) join the probability functions for the sum of the success entries for each of the Boolean functions; 5) form the product probability of the success entries over all of the Boolean functions; and 6) substitute the time-dependent component functions into this product. The result is a probability of success function for the whole system as estimated from the starting point. This function also might have been constructed from any later time point, but the new state conditions must be used. The presence of a failed unit would obviously reduce the unit's probability of success to zero. Consider the example shown in Fig. 1 with logic in Table 1.

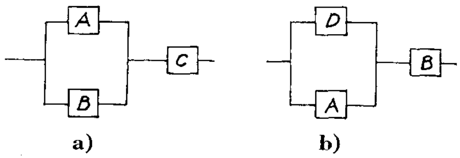

Fig. 1 a) Phase I structure; b) phase II structure.

The probability of success (or fail) for each row entry for each column is formed by taking the product of the variable state occurrance probabilities for each argument of the function. For example,

$$P_{1,1} = P_A P_B P_C \qquad P_{1,6} = P_A(1-P_B)P_C$$

where P_A, P_B, P_C, and P_D are the probabilities of success of the components A, B, C, and D.

The sum of the row entry probabilities for all of the rows having a value 0 for the specified phase function gives the probability of success for that phase. Thus, the probability of success for phase I is

$$P_1 = P_{1,1} + P_{1,2} + P_{1,5} + P_{1,6} + P_{1,9} + P_{1,10}$$

similarly for phase II probability. Of course, a simplification can be made by considering the minimum number of table entries for each set of arguments, but the principle is unchanged.

Finally, the product probability $P = P_1 P_2$ gives the probability of success of the system. If the probabilities of the components are given explicitly, say in the form $P_A = e^{-\lambda\tau}$ a simple substitution will give the explicit probabilities of success.

Now, consider the general case. Suppose that there are m phases of a mission. Let the probability of success of the ith phase be denoted by P_i. Since the phases necessarily occur in series, the probability of total success is given by $P = P_1P_2 \ldots P_m$. Let the ith phase be characterized by an organization of n_i elements, the Boolean equation for which is

$$B_i = B_i\ (A_1, A_2 \ldots, A_{n_i})$$

Its associated logic table and probability functions are given in Table 2.

Table 1 Logic data: where 0 = success and 1 = fail

A	B	C	D	$(A \cup B) \cap C$	P_{ij}	$(D \cup A) \cap B$	$P_{2,j}$
0	0	0	0	0	$P_{1,1}$	0	$P_{2,1}$
0	0	0	1	0	$P_{1,2}$	0	$P_{2,2}$
0	0	1	0	1	...	0	...
0	0	1	1	1	...	0	...
0	1	0	0	0	...	1	...
0	1	0	1	0	...	1	...
0	1	1	0	1	$P_{1,7}$	1	...
0	1	1	1	1	...	1	...
1	0	0	0	0	...	0	...
1	0	0	1	0	...	1	...
1	0	1	0	1	...	0	...
1	0	1	1	1	...	1	...
1	1	0	0	1	...	1	...
1	1	0	1	1	...	1	...
1	1	1	0	1	...	1	...
1	1	1	1	1	$P_{1,16}$	1	$P_{2,16}$

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