An Electrostatic Roll Sensor for Supersonic Vehicles Part I: Feasibility and Flight Tests

J. L. Frierson* and F. G. Moore†
Naval Surface Weapons Center, Dahlgren, Va.
and
R. L. Van Meter‡
Motorola, Inc., Scottsdale, Ariz.

A simple, rugged, and low-cost roll sensor developed for model aircraft has been adapted for use on supersonic missiles and projectiles. Pairs of ionizing elements placed symmetrically about the vehicle roll axis sense the vertical electrostatic gradient in the earth's atmosphere, which produces a voltage differential between sensors proportional to their vertical separation distance. Recessing the sensors below the supersonic freestream allows adequate ionization to occur and thus maintains sensor sensitivity. Large separation distances between individual sensors are not required to generate a sufficient voltage differential. Several missile and projectile flight tests were conducted at velocities up to Mach 2.1, roll rates between 2-13 Hz, and altitudes ranging from sea level to 3000 ft. Under these test conditions, sensor accuracy was generally within ±5 deg of true roll position.

I. Introduction

A LIMITING factor in the successful design of a low-cost guidance package for supersonic missiles and projectiles is often the mechanical gyro. In addition to cost, the packaging and power requirements are often prohibitive in low-cost applications. Lengthy start-up times and the need to initialize the system can also impose severe restrictions on system performance. In the emerging field of gun-launched guided weapons, the setback forces at firing (up to 10,000 g's) are an additional major constraint to any system containing sensitive moving parts. Although there are alternatives to the mechanical gyro presently available, many of these designs still share a number of the limitations noted above.

This paper is concerned with efforts to explore the feasibility of using the earth's electrostatic field to determine the roll position of a missile or projectile moving at supersonic velocities. Since no moving parts are required, a system of electrostatic sensors could provide a supplement to mechanical gyros. The technology developed for a successful roll sensor could then be applied to sensing other attitude changes in the vertical plane as well.

II. Theory and Background

The earth's atmosphere contains an electric field that is usually oriented vertically and whose intensity is fairly constant, (100-200 V/m) at altitudes up to 4000 feet.[1,2] Above this altitude, the potential gradient decreases rapidly owing to a higher conductivity of the atmosphere above the convective mixing layer.

In the presence of this vertical potential, a sensor located at a higher altitude will read a more positive voltage with respect to a similar sensor located at a lower altitude. The magnitude of this voltage differential will be proportional to the vertical separation distance of the sensors. If a pair of these sensors are affixed symmetrically on opposite sides of a missile or projectile, the vertical separation distance between the two sensors will change as the missile rolls during flight. The sign of the voltage differential between the two sensors will vary from positive to negative depending on which particular sensor is "up." The absolute value of the voltage differential should reach a maximum when the sensors lie in the vertical plane and a minimum (zero) when the sensors lie in the horizontal plane. Ideally then, a steadily rolling airframe should produce a sinusoidal voltage output from each sensor pair as a function of time that can be converted to instantaneous roll position. The sensitivity of the electrostatic sensor is enhanced in our case through the use of alpha particle emitters to ionize the air near each sensor, thereby making better electrical contact with the atmosphere.

This concept is not entirely new, having been first conceived and demonstrated in the early 1970's by Maynard Hill of The Johns Hopkins University Applied Physics Laboratory. Hill[2] has demonstrated the ability of an electrostatic autopilot system to roll-stabilize model aircraft and light aircraft by mounting a sensor on each wingtip. However, these tests were obviously conducted at relatively low velocities and altitudes and with a minimum separation distance of several feet between sensors. In addition, the thrust of Hill's work was not to determine real-time roll position, but simply to null out any voltage differential, thus maintaining the aircraft's wings in a level position. To be successfully adapted to small, high-performance missiles and projectiles, however, these sensors must function under conditions of high Mach number and roll rate with separation between sensors measured in inches instead of feet.

At the time this effort was initiated, it was thought that the sensors would not function at supersonic velocities since the ion cloud surrounding each sensor would be immediately swept away by the freestream, thereby reducing sensor sensitivity to unacceptable levels. In fact, the work of Hill and others[3] had previously indicated that the sensor output would decrease rapidly at velocities greater than several hundred feet per second. However, since the signal strength, i.e., the amount of current collected by the sensors, is related to the concentration and residence time of the ions in a thin layer above the sensors, it seemed likely to the authors that the sensors might continue to work at supersonic flight speeds if

Presented as Paper 77-1067 at the AIAA 1977 Guidance and Control Conference, Hollywood, Fla., Aug. 8-10, 1977; submitted Sept. 12, 1977; revision received Dec. 27, 1977.

Index categories: LV/M Guidance; LV/M Command and Information Systems; Guidance and Control.

*Aerospace Engineer, Weapons Systems Department.

†Supervisory Aerospace Engineer, Strategic Systems Department. Member AIAA.

‡Electronics Engineer.

they were protected from the freestream velocity by mounting them flush in the boundary layer or recessed in a cavity below the vehicle's surface. Possibly, then, the local flow velocity near the sensor would be low enough to allow time for more charge separation and consequently, to provide larger signals with respect to the sensor's orientation in the electric field.

III. Test Objectives

The overall feasibility of this concept hinged on the answers to the following two basic questions: 1) Will the sensors work at all at supersonic velocities? 2) What will be the accuracy of the sensor output? Since a comprehensive and accepted analytical model of the supersonic ionization/flowfield interaction was not available at the time, it was decided that a limited but concise flight test program would be the most direct means of answering the questions above and establishing feasibility. Accordingly, it was decided to design, fabricate, and test fire several instrumented missiles and projectiles at the NSWC/Dahlgren test range. Each test vehicle would carry several electrostatic sensors plus a roll-sensing device of known accuracy to be used as reference.

IV. Missile Test Configuration

A missile flight-test vehicle was assembled using available hardware. An inert Zuni warhead was mated to a surplus Sidewinder rocket motor, with the warhead explosive replaced by a 15-channel telemetry package (Fig. 1). Up to six pairs of electrostatic sensors were then mounted either flush on the motor or tail surfaces, or in 0.25-in. deep recessed cavities on the nose section. One pair was even wrapped around the leading edge of two tail fins. Sensors located 180 deg apart in the roll plane were paired to produce one channel of raw data. A set of four sun sensors evenly spaced around the nose provided the true roll position reference. Small trim tabs were attached to each tail fin to generate a nominal roll rate of about 3 Hz. The complete test vehicle measured 105 in. in length and weighed 120 lb at launch.

To measure the potential gradient across each pair of sensors, the basic electronic circuit developed by Hill[2] was used with the exception of a field-effect-transistor (FET) input operational amplifier at the output of the ionizing unit as shown in Fig. 2. These ionizing units were Staticmaster model 2 μ 500 (500 microcurie polonium alpha source) with a half-life of 138 days. The required voltage from the circuit to frequency modulate the telemetry voltage control oscillator (VCO) by $\pm 7.5\%$ was ± 2.5 V, respectively. The output of the 741 operational amplifier in Fig. 2 is $10\,[E_l - E_2]$.

Figure 3 shows the nominal ballistic trajectory chosen for the missile flight test series. Maximum velocity at motor burnout is Mach 2.1 with apogee at 3000 ft. A maximum of 8 s of supersonic flight data are available from each test flight. The test vehicle is fired from a ground level fixture at 20 deg elevation angle using a standard Sidewinder launch rail.

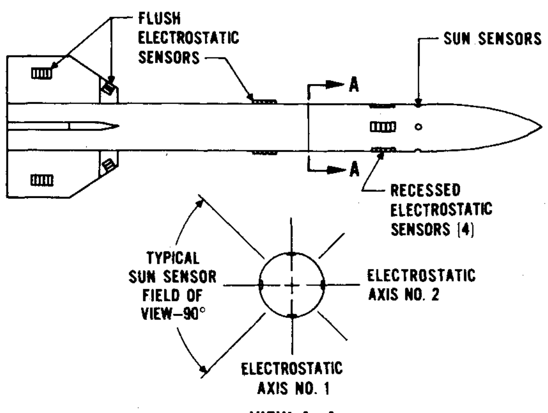

Fig. 1 Missile flight-test configuration.

V. Missile Test Results

Five missile flight tests occurred between April and December 1974 under clear skies. The test vehicles performed as expected, with flight times averaging within 5% of the nominal 27 s. Overall, excellent telemetry data were received in the Mach number range 0.6-2.10. Typical roll rates were 1-3 Hz.

Figure 4 shows typical output from two orthogonal pairs of recessed nose sensors along with the sun sensor channel as reference. Superimposed on this sun sensor output are symbols indicating for this particular test, the points in each roll cycle where a given electrostatic axis actually lies in the vertical plane. The corresponding maxima and minima as detected by the electrostatic sensors are shown to be in close agreement with the sun reference. The actual discrepancy between these outputs is defined as electrostatic error angle, ϵ. Also, note that the two orthogonal electrostatic outputs are in proper phase with each other as evidenced by the 90-deg roll offset between channels. Similar data were obtained from the flush-mounted sensor pairs, except that various amounts of noise were superimposed over the clear sine wave shown here. Thus, for brevity, only data from the recessed sensors will be discussed in the remainder of this text.

Due to the high resistance in the sensor circuitry of Fig. 2, some estimate of signal-to-noise ratio was required to help establish feasibility. Supersonically, typical $E_l - E_2$ magnitudes between recessed sensors was about 0.12 V through a bandwidth of 2000 Hz, with one half $E_l - E_2$ assumed to be across each 200 Mohm resistor. (The characteristics of the FET input op-amps contribute only a negligible load to the ionizer-resistor combination.) Calculations of input noise under nominal test conditions yield rms noise voltages on the order of 0.1 mV for each branch of the sensor circuit. This results in a substantial signal-to-noise ratio of approximately 55 dB from each sensor.

Two general conclusions were immediately evident from these tests: 1) As theorized, the strongest and clearest data were definitely produced by the sensor pairs recessed in the

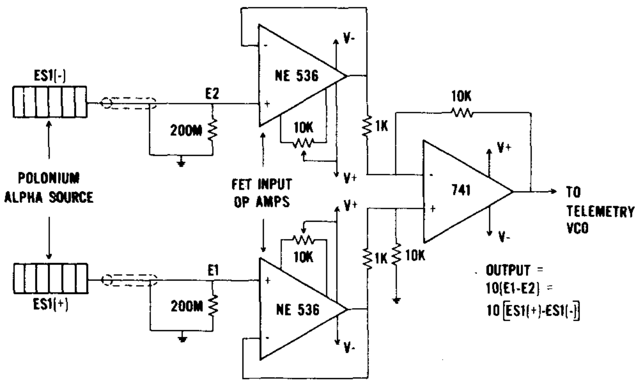

Fig. 2 Gradient detection circuit.

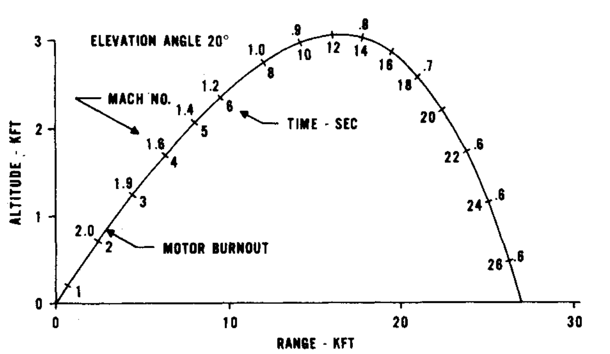

Fig. 3 Nominal flight trajectory.

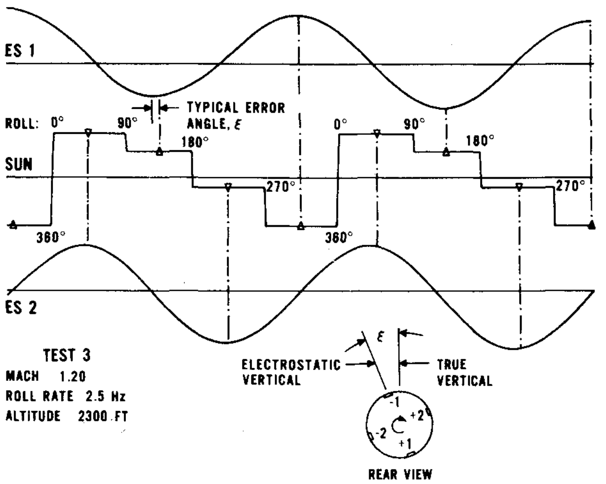

Fig. 4 Typical sensor outputs.

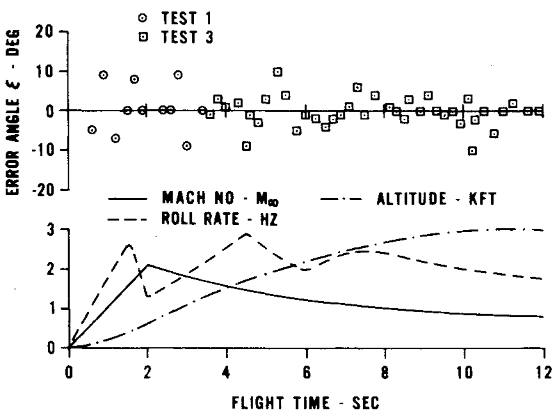

Fig. 5 Missile supersonic flight data.

missile nose, even though these sensors had the smallest separation distance – approximately 4.5 in. 2) However, even the much noisier data from the flush-mounted sensors on the body and tail also displayed the expected sinusoidal pattern. In addition, all the flush-mounted sensors, regardless of location, showed essentially the same signal strength and noise levels at any given point in the flights.

Having demonstrated that a recessed sensor would work at supersonic speeds, further analysis focused on the nature and magnitude of any roll angle errors present in the data. Of particular interest were the effects of changing Mach number, altitude, and roll rate on electrostatic error angle. Recall that in this case, the electrostatic error angle is defined as the roll angular difference between the vertical plane as sensed by the electrostatic circuit and the "true" vertical plane obtained from the sun sensors.

Data from two test flights, with identical sensor location and nearly identical trajectory characteristics were combined into a composite flight history encompassing the complete Mach number range. Figure 5 presents the electrostatic error angle along with the previously noted parameters of interest. The electrostatic error angle is shown to be generally less than ± 5 deg with respect to the sun sensor reference throughout the flights, with all data within ± 10 deg of the reference. In actuality, this error angle is believed to be essentially zero, since the magnitude of this error band is approximately the magnitude of other known error sources inherent to this test setup. Primary among them are the sun sensors themselves, whose accuracy as a reference depends on maintaining relatively steady roll rates and a precise knowledge of the sun's actual position with respect to the missile at any point in the flight. Additional, although smaller, errors were no doubt

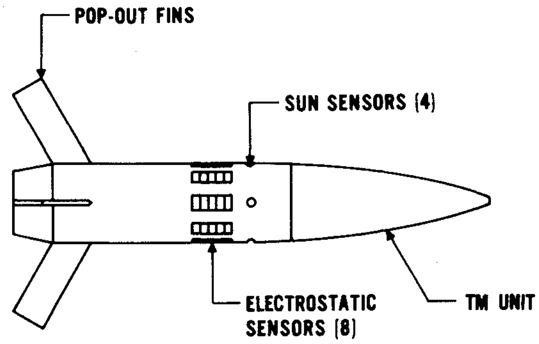

Fig. 6 Projectile flight-test configuration.

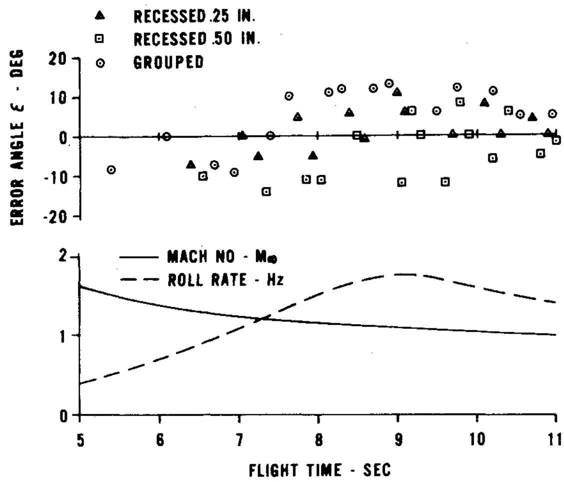

Fig. 7 Projectile supersonic flight data.

introduced during data reduction, since the precise points of sinusoidal maxima and minima were sometimes difficult to determine. In actual practice, however, random roll errors of even this magnitude would have little effect on the overall performance of many low-cost guidance systems.

Also note from Figure 5 that the magnitude of the error angle apparently is not affected as the Mach number decreases from 2.1 to 0.6, even near sonic velocity where the freestream conditions may be unsteady. Similar insensitivity is observed with respect to the changes in roll rate per se, as opposed to the effects of roll acceleration on data reduction as discussed previously. Finally, as expected, the altitude variations experienced on these tests had no noticeable effect on the electrostatic output, and should be considered of minor importance below 5000 ft.

VI. Projectile Test Configuration

One question yet to be answered was the possible application of similar sensors to gun-launched projectiles. The primary constraints in this application are the extremely large setback forces at firing (up to 10,000 g's) and the physical limitations on placement imposed by the gun barrel. Thus, an electrostatic sensor circuit, sun sensors, and telemetry pack were prepared for testing in a 5-in.-diameter fin-stabilized projectile then undergoing ballistic flight tests at NSWC/Dahlgren. The projectile, shown in Fig. 6, is about 30 in. long and weighs 50 lb.

Also of interest for this test were the possible effects of sensor recess depth and sensor grouping on electrostatic accuracy. Therefore, four sensor pairs were evenly spaced around the projectile circumference alternately recessed either 0.25 or 0.50 in. into the body surface. Sensors mounted 180 deg apart were paired to provide four channels of raw data. In addition, four adjacent sensors were compared with the opposite four sensors in an attempt to increase sensitivity.

VII. Projectile Test Results

The projectile flight test occurred in July 1975 on a cloudy day. Initial velocity at the gun muzzle was Mach 2.4 after a setback load of 7700 g's. The nominal trajectory profile was very similar to that of the previous missile tests. As far as is known, this was the first operating electrostatic sensor circuit to survive the high-g gun environment. Due to a shift in the telemetry carrier frequency at launch, no usable data were received for the first 5 s of the flight. Thus the maximum velocity for which data is available was March 1.5. Peak roll rate after fin deployment was about 2 Hz.

The electrostatic data obtained from this test were of the same form as the previous rocket tests, although somewhat noisier. Figure 7 shows the same sensor error angle for the supersonic portion of the flight from which data were available. Although larger than the previous rocket tests, the error angle is shown still to be generally less than ± 10 deg, and entirely within a ± 15-deg band. Two particular factors are thought to have degraded the accuracy of this test. First, and most importantly, several of the individual sun sensors apparently began to fail during flight, thereby shifting the roll reference points at a time when the roll rate was constantly changing. Also, a storm front that was approaching the range at test time could have been distorting the vertical electrostatic gradient in the test area.[2,4] Thus, the apparently larger electrostatic error angles shown here are not considered excessive in light of these and previously noted error sources.

A final note concerns the effects of sensor depth and grouping. The data of Fig. 7 seems to indicate that, within the accuracy limitations of this test, there was no significant increase in sensor accuracy gained by either deeply recessing individual sensors or grouping of adjacent sensors.

VIII. Conclusions

The overall results of the electrostatic flight-test program were very encouraging. A hybrid test missile and telemetry unit were assembled and successfully test fired. The same basic sensor system also survived the rigors of gun launch. The electrostatic sensors have been proven to work at supersonic speeds by simply recessing them below the freestream. The expected sinusoidal output was obtained up to Mach 2.1. Roll position as determined by the electrostatic sensors was generally within ± 5 deg of the true roll position, even including test errors from all other sources. This accuracy was not significantly affected by the changes in Mach number (0.6-2.1), altitude (0-3000 ft), or roll rate (2-12 Hz). The best data were also obtained from the sensor pairs with the minimum separation distance-only 4.5 in. Signal-to-noise calculations using actual test data indicate that sufficient signal strength is generated by the sensors under the conditions tested.

In conclusion, these results clearly demonstrate the feasibility of using electrostatic sensors on supersonic vehicles. Such a system is simple, low-cost (about $25 in parts), and rugged enough for gun-launched projectile applications. Response is immediate, since the start-up time is essentially zero and no initialization is required. In fact, a simple electrostatic circuit can be used in conjunction with alternate guidance schemes to provide initialization, resolve up/down ambiguities, or update the vertical reference. Similar technology can be adapted to pitch-plane determination as well.

As a result of this effort, a theoretical analysis of the ionization/flowfield interaction was undertaken at NSWC/White Oak to develop an accurate model of this electrostatic phenomenon. Wind-tunnel tests were also planned to obtain additional test data under more controlled conditions. A discussion of these efforts will be presented in "Part II: Theoretical Analysis and Experimental Results."

References

[1]Chalmers, J. A., *Atmospheric Electricity*, Pergamon Press, New York, 1967.

[2]Hill, M. L., "Introducing the Electrostatic Autopilot," *Astronautics and Aeronautics*, Vol. 10, Nov. 1972, p. 22.

[3]Hill, M. L. and Hoppel, W. A., "Effects of Velocity and Other Physical Variables on the Currents and Potentials Generated by Radioactive Collectors in Atmospheric Electric Fields," *Proceedings of the Fifth International Conference on Atmospheric Electricity*, Sept. 1974.

[4]Markson, R., "Practical Aspects of Electrostatic Stabilization," *Astronautics and Aeronautics*, Vol. 15, April 1974, p. 44.