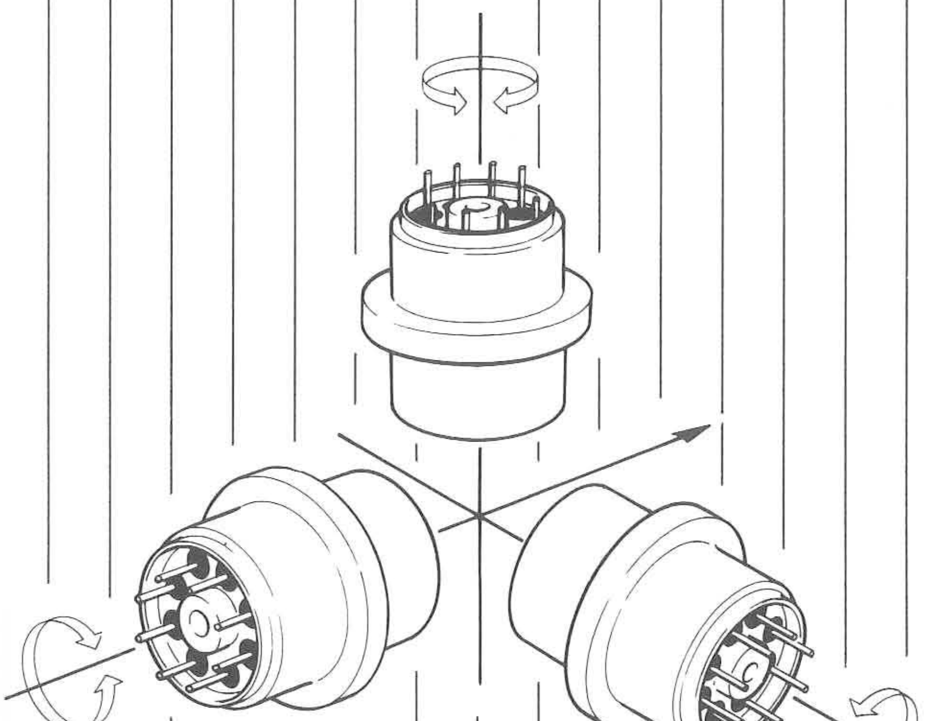
GEC AVIONICS

START



A Solid State Broad Application Gyroscope

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Preface

Innovative START for the 1990's

START is unlike any other gyroscope currently in existence. It is solid state in that it has no moving parts such as the spinning wheel, gimbal and electrical pick–off that are used in conventional gyros. It is extremely rugged having successfully completed experimental trials up to 25000g. It has no wear–out mechanism and therefore has very long life with zero maintenance. START is ready for use within 0.2 of a second from switch–on as compared with conventional gyros which in general have a ready time of between 10 and 30 seconds. It is small, lightweight and uses little power enabling long term operation from a battery should a generated electrical supply not be available. The mechanical simplicity of the design, which is based on a steadily pulsating cylinder (see paras 4 and 5 contained in the narrative), provides the potential for mass production manufacturing techniques and a very low unit production price, which is estimated to be one tenth of that for conventional rate gyros with similar performance.

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"START" – A SOLID STATE BROAD APPLICATION GYROSCOPE

1. Abstract

'START' is an all solid state angular rate sensor which began development in the early 1980's, for weapons applications. Prototypes appeared in 1987 and the combination of ruggedness and simplicity opened up many new applications. The sensor, applications and performance achieved are described in the following paragraphs.

2. Introduction

In the early 1980's, GEC Avionics foresaw a requirement to replace weapons using a ballistic trajectory (unguided weapons) with types which were guided into a target area and steered to a target. Such weapons must contain motion sensors and these sensors would dominate the cost of the additions needed to provide flight control and guidance. Apart from the technical requirements for performance in the military environment, the components were required to satisfy all the following criteria:

(i) Low Cost

(ii) Long Shelf Life with Zero Maintenance

(iii) Very Rapid Start–up

(iv) Small and Lightweight

(v) Very High Shock Resistance.

GEC Avionics concluded that new types of sensor were needed to satisfy all these requirements and a research programme was carried out to identify suitable techniques on which to base the sensor design. The search concentrated on angular rate sensing methods and a technique emerged which is embodied in START (Solid sTate Angular Rate Transducer).

During the later development phases for START, several new applications emerged, many of them taking advantage of the fact that the device has no obvious wear–out mechanism and the principal performance parameters can be easily tailored to the application. Most of these new uses are non–military, thus leading to a truly wide spectrum of employment.

The narrative begins with an outline of the development phases of the START programme, followed by a description of the principle of operation. Current status and performance achieved to date are then described. This is followed by a summary of the areas of application for which START is either used or projected for field tests, and concludes with the expected timescale for moving from prototype to large quantity production.

3. Main Phases of Development Programme

In order to concentrate the initial search for suitable techniques for measuring rotation rate it was essential to target values for the principal parameters. The requirement to survive munition launch conditions dictates a shock resistance of at least 15,000 g. In addition to functioning normally immediately after this level of shock, the sensor must not be upset by the vibration spectrum encountered in high speed missile flight. Target values for the other important parameters are shown in Table 1.

Table 1. Initial Target Values For START

PARAMETER	TARGET VALUE
Price	£250 to £500
Reaction Time	Less than 0.1sec
Weight	Less than 75 gm
Power Consumption	Less than 1W
Zero Offset	Less than 5°/sec
Drift Stability	Less than 0.5°/sec
Linearity + Scale Factor	1% to 5% (By Selection)
Bandwidth	*Up to 80 Hz
Threshold	Less than 0.1°/sec
Measurement Range	Greater than 500°/sec

* Preferably it should be simple to select a bandwidth in the range d.c. to 10 Hz minimum and d.c. to 80 Hz maximum.

After 18 months of investigation, a technique was chosen based on the predictability of the deflection of an established vibration pattern in a cylinder, when the cylinder rotates about its principle axis. This is not a new idea, but the basic sensor has comparatively high temperature coefficients of bias and scale factor if low cost materials are used. The strategy with START is to use a single micro–electronic circuit to provide all the services needed for operation and also the inherent thermal compensation needed to achieve the performance targets. The additional cost for this compensation is trivial in mass produced electronics.

The development programme initially concentrated on establishing confidence that the chosen technique would yield the required performance within the price, size, power etc., constraints. Fig. 1 shows the main activities in the programme to date and the confidence–establishing period is the first four years. During this period the effort was concentrated on choice of materials and assembly methods for the vibrating cylinder. The electronics were brass–board standard.

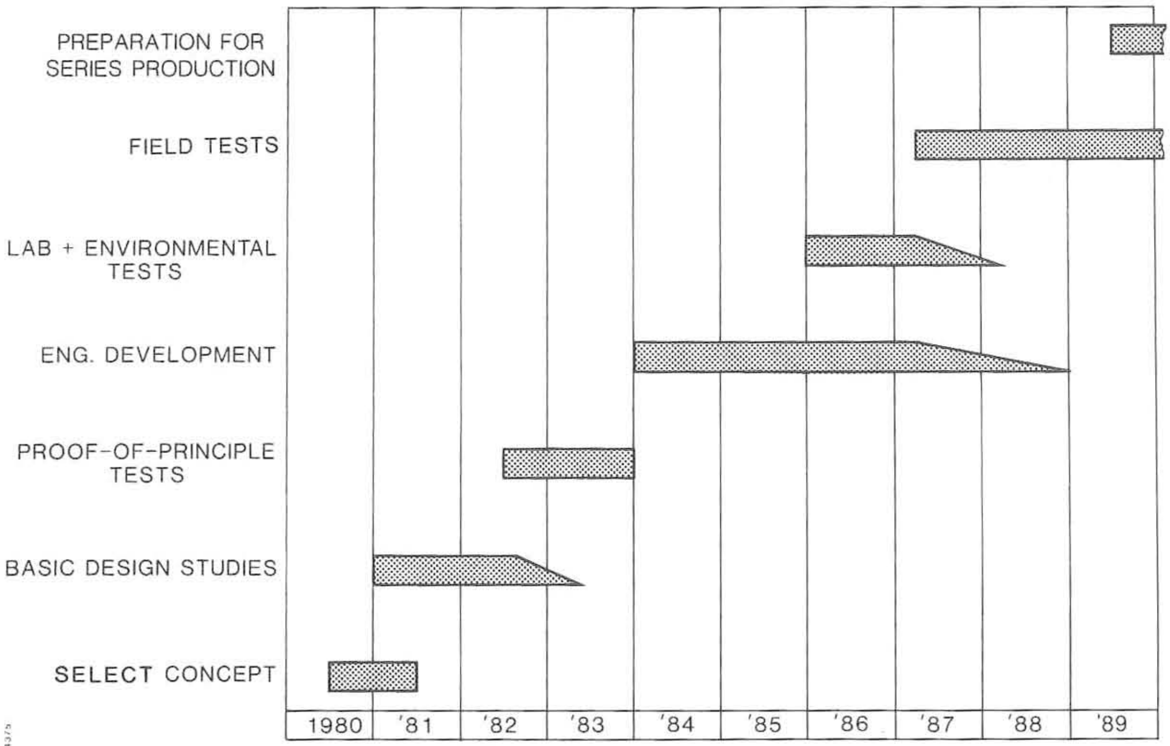


Fig. 1 START Development Timescale

In 1984 the emphasis moved to the engineering detail required for miniaturising the cylinder and refining the electronic design in a more rugged form. During the period 1984 to 1987, several batches of sensors were designed and made to assess the merits of different material combinations and assembly techniques. In all cases, a prime criterion for acceptability was the consistency of the temperature coefficients of the cylinders in any one batch.

In 1987 field trials of engineering prototypes began and typical cylinders were tested for shock survival at increasing levels up to 25,000 g. At this time the electronics were not suitable for such tests. The success of these tests led to a rapidly widening range of applications which provided the incentive to design a rugged cylinder/electronics combination. As these were still prototypes for evaluation, the electronics were packaged in a hybrid micro–electronic device which could be easily modified for different applications. The module has a minimum shock resistance of 10,000 g.

To date more than 100 START rate sensors are currently being tested in a variety of uses, in several countries.

4. Principle of Operation

Fig. 2 shows the schematic arrangement for START. The vibrating element is a cylinder, chosen for its symmetry about the axis of measurement. The vibration pattern is established using piezo electric transducers AA and BB in a phase locked loop. The transducers are electrically connected as parallel pairs, but for diagramatic simplicity a single connection only is shown. The full circle is the cylinder cross–section when at rest. The two dotted outlines show, much enlarged, the limits of the deflection when the cylinder is vibrating. The choice of high efficiency transducers and low loss material for the cylinder results in a very small power requirement to sustain the oscillation, approx 10 mW.

Positioned mid–way between the A and B transducers are piezo electric crystals CC which are ideally on the vibration nodes of the cylinder when it is not rotating. The oscillatory strain in the cylinder at the C transducers is measured by phase sensitively detecting their outputs with respect to the oscillation at AA. When the cylinder rotates about its principle axis, the nodes tend to rotate away from the 'C' positions by an angle related to the rate of rotation. The oscillatory strain in the cylinder at points C is therefore a measure of the angular rate about the cylinder axis and this is directly indicated by the output of the phase sensitive detector.

This basic scheme works satisfactorily for steady angular rates but has a very narrow bandwidth when varying rates are applied. This makes it unsuitable for a practical rate sensor. The function of the DD driver transducers is to overcome this drawback by feeding back an amplified, frequency dependent version of the envelope of the signal at the points C. With suitable choice of gain and frequency response in this negative feedback loop, the characteristics of the simple system are modified to a form determined by the transfer function of the feedback path. In particular the bandwidth of the unit as a rate sensor is controlled by this transfer function thus allowing a wide range of performance characteristics to be obtained from a single design of cylinder, solely by changes of the electric circuit.

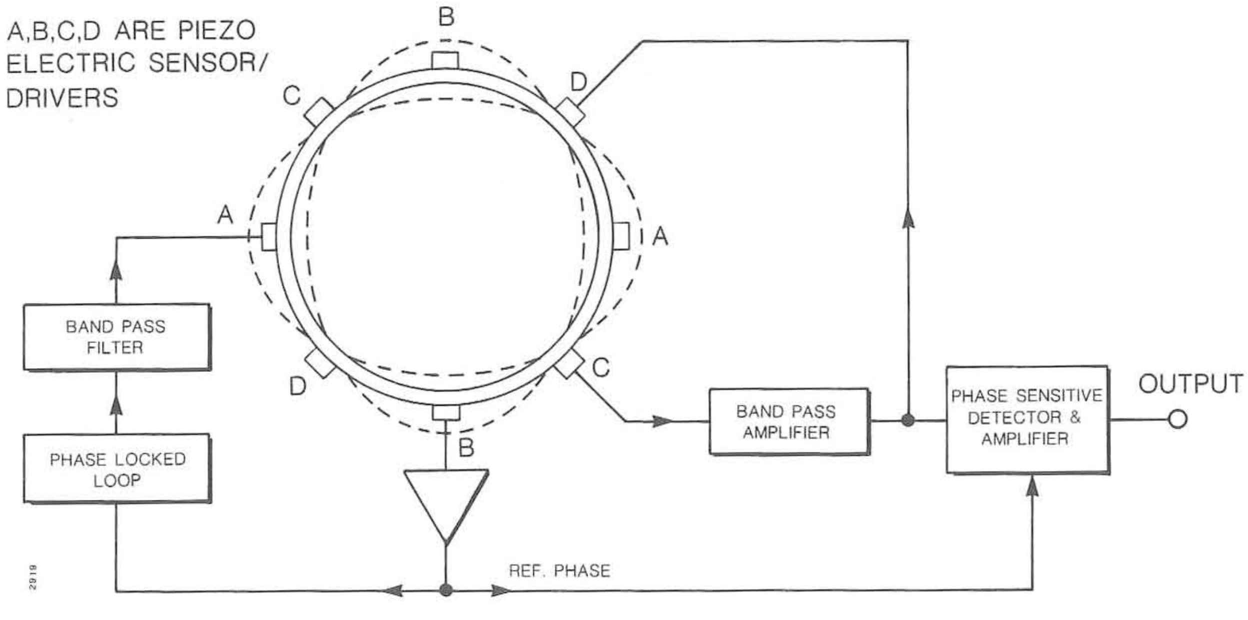


Fig. 2 'START' Gyro Scheme of Operation

In Fig. 2 the electronics are shown as functional modules. In practice these are contained in the small circuit unit shown in Fig. 3.

The maximum angular rate that START can measure is dependent on two factors. First there is an inherent limit determined by the cylinder material and drive capability of the piezo electric sensors. The second limit occurs when the electronic amplifier in the output circuit saturates. The first limit is much greater than the second, so that the practical range of measurement is set by the electronics. A change of gyro scale factor (degrees/sec per volt) is obtained simply, by changing the gain of the output amplifier. The design of the cylinder, drive electronics, etc. is not affected. A benefit of this scheme is that the inherent threshold and drift offset of the gyro vary little as the measuring range is increased or decreased. The detection threshold is theoretically very low but in practice it is determined by the signal/noise ratio at the C transducers.

Gyro offset and offset stability is a more complex problem dependent on geometric accuracy of the cylinder/transducer assembly, the thermal characteristics of the materials and the stability of the electronic circuit parameters. The design philosophy for START is to minimise the temperature coefficient of offset inherent to the cylinder and compensate for the remaining effect with a coefficient of opposite sign in the electronics.

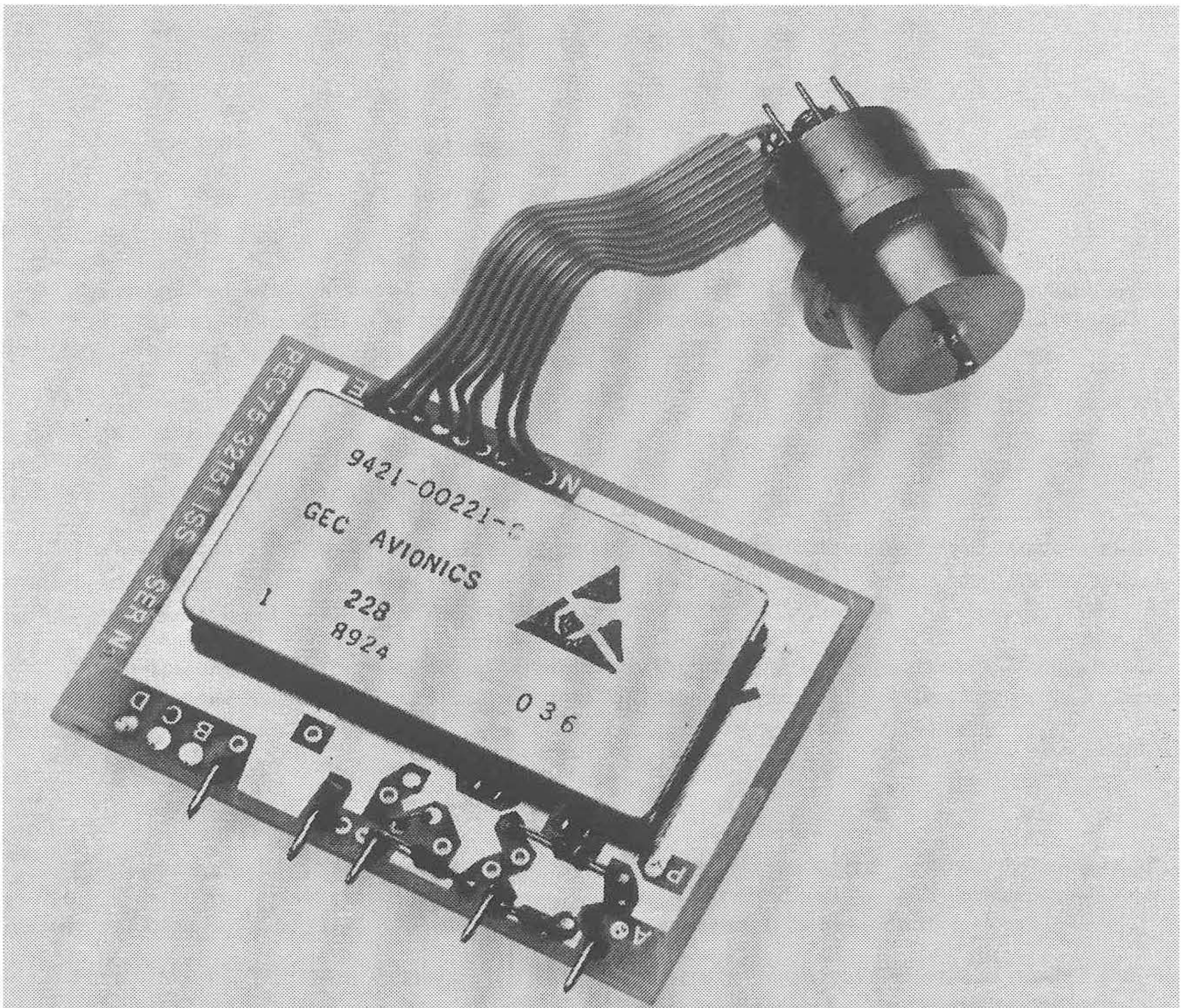


Fig. 3 START Cylinder and Hybrid Electronic Module

5. Current Status of START

The design of the cylinder has changed little in the past 2 years. The emphasis has been on the choice of machining and assembly techniques which yield a consistent product.

The electronic module has evolved considerably during this time from the original basic circuits on a small printed circuit board to the final more sophisticated version of a hybrid micro–electronic circuit mounted in a rugged metal case. Fig.3 shows the finished cylinder, the hybrid electronic module and the connecting ribbon cable. The hybrid is fixed on a simple printed circuit board for convenience of mounting the associated scaling components.

More than 50 sets based on this standard have been sold for evaluation by potential users. The following summary of achievements mostly refers to data from this latest group of sensors.

5.1 Physical Status

The cylinder dimensions are 24 mm (1.0 in.) diameter, by 28 mm (1.1 in.). The hybrid measures 32 mm (1.26 in.) by 57 mm (2.25 in.) by 6 mm (0.25 in.).

The weight of each component is:–

Cylinder	25 gm
Hybrid	27 gm
P.C.B.	13 gm
Total	65 gm (2.3 ounces)

5.2 Electrical Status

The present design requires two power supplies +15V d.c. and –15V d.c. with a typical total power consumption of 1.2 watt. This value is independent of the rate being measured. An analogue d.c. output is provided with a minimum linear range of +10V to –10V.

5.3 Sensor Performance

5.3.1 Measurement Range and Scale Factor

The angular rate to produce 10V output is determined by the value of two resistors on the printed circuit board, external to the hybrid. The range of adjustment is from 40°/sec full scale (250 mV per °/sec) to 1000°/sec full scale (10 mV per °/sec).

For each sensor, the scale factor variation with temperature is approximately linear and can therefore be simply compensated in the electronics using a temperature sensor located at the cylinder. With this compensation the maximum variation of scale factor over the range –40°C to +80°C is 5%, relative to the room temperature value.

5.3.2 Linearity

Careful measurement at constant temperature shows that the inherent linearity of START over the output range +10V to –10V is better than 0.1% of full scale. However, as the scale factor and bias vary with temperature, this value for linearity is rather academic and a practical value to use for design purposes is 0.25% of full scale.

For rotation rates greater than the linear range the output saturates at around plus or minus 12V depending on the sense of rotation. Tests with input rates up to 20 times full scale show no change in this saturation characteristic.

5.3.3 Zero Offset

Each sensor is adjusted to have a fixed component of offset of less than 2°/sec, at room temperature. The second component is the variation with temperature about this nominal value. Over the temperature range –40°C to +80°C, this variation is within 1°/sec of the nominal value.

5.3.4 Readiness Time

START is ready to measure angular rate 0.25 sec after the application of power. There is a short settling time for the offset and this is within 0.2°/sec of its steady state value not later than 0.5 sec from switch–on.

5.3.5 START Transfer Function

As stated in Section 3, the relationship between input rate and output voltage as a function of frequency, is primarily determined by the transfer function of the feedback path between the C and D piezo–electric transducers. The form chosen for the sensor response is that of a simple lag, $V_o = \frac{K\Omega}{1+\omega T}$

V_o = output amplitude
$\Omega \sin \omega t$ = applied angular rate
T = sensor time constant

To maximise the range of applications for the sensor it is necessary to make T small to provide as wide a bandwidth as possible. In earlier experimental circuits it was demonstrated that stable performance is obtained with a time constant of 1.7 msec that is a 3dB bandwidth of d.c. to 90 Hz.

The time constant used in the hybrid circuit is 2.5 msec, providing a bandwidth of 56 Hz.

5.3.6 Threshold of Rate Detection

Unlike spinning mass rate sensors the START mechanisation has no stiction equivalent so that the threshold value is practically determined by the low frequency noise on the output due to circuit noise and temperature fluctuations. Under closely controlled experimental conditions, this value is around 10°/hr. In a practical application a value of 0.02°/sec is more realistic.

5.3.7 Acceleration Sensitivity

There are three different aspects of sensor acceleration sensitivity:

(i) Effect of linear acceleration on performance, particularly on the zero offset.

(ii) Survival of very high 'g' shock levels.

(iii) Effect of sinusoidal vibration on performance.

The effect of sustained acceleration or 'g' sensitive drift was originally measured using a high speed centrifuge producing up to 500 g. The accuracy of this method is limited by uncertainty of the amount of the centrifuge rotation which is measured by the sensor, due to deflection of the sensor mount under the high acceleration. These tests yielded a worst case value of 0.05°/sec/g. Later tests on one sensor indicate that the sensitivity is less than 0.01°/sec/g. Tests to establish a typical value will be made but the change in emphasis for START applications has reduced the priority for this.

The ability of START to withstand shock was initially tested on typical cylinders, in machines which simulated launch from a cannon. Acceleration up to 25,000 g was applied along and across the rate sensing axis. No cylinder suffered any damage and worst parameter change was a zero offset change of 2°/sec.

In subsequent tests a triad of complete sensors, cylinder plus electronics, was fired from a large gun. The maximum acceleration was approximately 5,000 g and all three gyros functioned normally throughout the flight of the weapon. On retest in the laboratory, the only parameter change detected was a shift of 5°/sec on one sensor. The same triad was fired a second time under the same conditions. Again the performance was satisfactory and no significant parameter changes occurred this time.

The effect of sinusoidal vibration on performance was tested by subjecting a cylinder to vibration in the range 5 Hz to 9 kHz using a peak value of 20g. No measurable change of output occurred.

The ability to withstand long periods of vibration without failure was demonstrated when a batch of STARTs was used in the active suspension system of the Formula 1 Team Lotus racing cars. These sensors were fitted at the beginning of the 1987 season and operated throughout, without failure. The same sensors are still in use for developing the active suspension system.

6. Range of Applications for START

The summary of achievements in Section 5 shows that START is close to being suitable for the applications for which it was conceived, that is missiles and guided munitions. While these require a long shelf life without any maintenance actions, the operating life required is short. As START development progressed it became obvious that both shelf and operating life could be measured in tens of years as the device is mechanically very simple and contains no wear–out mechanism. This fact combined with the extreme ruggedness of START led to consideration of it being used in many non–military applications where normal gyroscopes had been ruled out on the grounds of cost and (relative) delicacy. The first such application was in Team Lotus Formula 1 racing cars as an essential component of the active suspension system. This experience encouraged Lotus to use START in their production car system. In addition, most other car system manufacturers have received STARTs for evaluation and field tests, during the past two years. Arctic trials were successfully carried out on two units, during the winter 1988/89.

Other applications being investigated are stability control systems for large vehicles and railway coaches where the ruggedness and reliability are prime reasons for considering START.

The use of START for robotic applications is proposed to exploit the combination of ruggedness, light weight and low power consumption.

A test has been underway for many months to use a START module to measure aircraft turning rates for flight data recording. This data must be reliably available during abnormal manoeuvres, therefore low power consumption, low cost and high reliability are the attractive parameters for this application.

The measurement of angular motion on the surface of the sea, in remote locations is a further application for which START has been selected in a buoy system of Seatex, Norway. Low power consumption and long life are technical imperatives in this case, with low cost important also.

It can be seen that uses on land, at sea, in the air and in weapons represents a truly wide spectrum of applications for START.

7. Plans for Large Scale Production

An important implication of the wide potential market is that total quantities and production rates are projected to be around 50 times greater than that envisaged when the programme began. In turn this will require the highest level of automation possible to produce consistently at the expected rate. The choice of techniques to implement this began a year ago and is progressing well. In particular, the electronic module for the production standard is a custom designed integrated analogue chip which is mounted directly on the pins of the cylinder.

When the production techniques have been chosen and proved in a pilot quantity, a major investment programme is planned. In order to meet the large scale requirements, production output must begin to grow rapidly from 1992 onwards and this is the objective of the current programme in GEC Avionics.

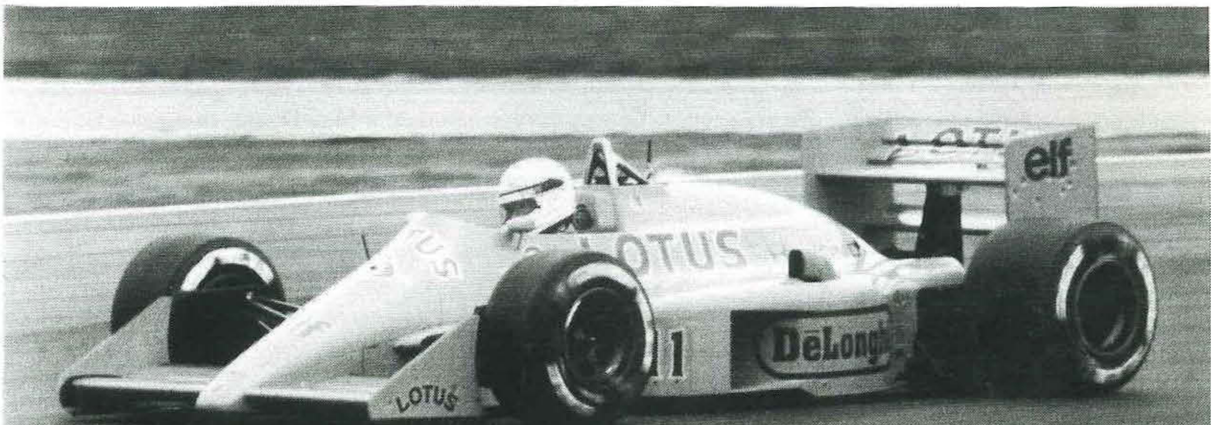
8. Conclusion

In 1980 the START rate sensor was originally conceived and developed for the then embryonic guided munition market. In the meantime the great reduction in the cost of digital electronics made possible a big increase in the sophistication of vehicle control systems, provided suitable sensors are available. The combination of characteristics necessary for the initial START applications proved to be very suitable for the vehicle control market and this has now been demonstrated practically in several cases. The production quantities required are large which justifies the development of a highly automated facility. This results in a low unit price which, in turn, widens the field of potential applications further.

The version of START which is currently being prepared to satisfy these requirements is the first generation of a new rate sensor technology in which the emphasis is to provide:–

- a wide performance range
- with very high shock resistance
- at the lowest price

If the pattern of other gyroscope developments is followed, a family of START type sensors is possible in which the relative emphasis of these three factors is varied to meet new requirements.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