Sensors and Actuators

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PREFACE

The following papers were presented at the 1988 International Congress and Exposition during the four sessions on Sensors and Actuators. Thanks are extended to all the authors for their contributions. The diversity and excitement of this rapidly developing area is apparent in their contributions. Special thanks are also extended to the Chairmen of the four sessions:

David L. Smith
Manager
Technology Development
Delco Remy Div.
General Motors Corp.

Allen H. Meitzler
Principal Research Scientist
Electronic Materials & Devices Dept.
Scientific Research Laboratory
Ford Motor Co.

William R. Seitz
President
Control Systems Technology

David S. Howarth
Staff Research Engineer
Electrical & Electronics Engineering Dept.
General Motors Research Laboratories
General Motors Corp.

To each of you who is interested in this area, I extend my invitation to participate in future sessions.

Stephen J. Citron
Sessions Organizer
Professor and Director
Engine Controls Laboratory
School of Mechanical Engineering
Purdue University

TABLE OF CONTENTS

880406

A New Era of Application for the Wiegand Effect

John E. Opie and Jon W. Bossoli
Echlin Mfg. Co.

ABSTRACT

This paper is presented to explain and demonstrate the most recent gains made in application techniques of the Wiegand Effect.

"Wiegand Wire" is a small diameter wire drawn from a magnetic alloy such as Vicalloy and secondarily processed by cold working so as to cause a gradient of magnetic hardness from its center to exterior. When exposed to magnetic fields of proper orientation, intensities, and sequence, substantial flux jumps will occur within the wire. These flux changes may be converted to an electrical pulse by interposing an inductive pick up-coil.

Being a bistable magnetic threshold device with a firing point of approximately 20 oersteds, the Wiegand Effect may be used to create self-powered pulsers which are essentially insensitive to speed and immune to most ambient magnetic field disturbances.

In addition to the extremely successful application as an encoding technique for " Access Control Cards", the Wiegand Effect has been applied in numerous commercial and industrial pulser designs where low speed, temperature extremes, and power considerations have made other technologies impractical.

Although a wide variety of magnetic field shapes and intensities will cause Wiegand Effect flux jumps, it has become apparent that certain field shaping techniques and packaging designs have advantages over others from the aspect of output pulse amplitude, general physical size of components, and immunity from permanent disruption by strong external magnetic fields. In order to best utilize the inherent advantages of the Wiegand technology, it is important that the optimal application techniques be identified and understood.

To this end, a great deal of development time has been devoted to investigating various magnetic excitation schemes and evaluating their results. The outcome was:

1. a three to four fold improvement in pulse amplitude under symmetric drive conditions;
2. a general reduction in physical component size; and
3. relative immunity from external magnetic field interference.

This paper will summarize the laboratory findings, demonstrate optimal field shaping techniques, and suggest designs for practical, cost effective pulsers.

INTRODUCTION

Historically, there have been two fundamental modes of magnetic excitation used to produce Wiegand pulses:

1) Symmetric mode - wherein positive and negative magnetic field excursions are of equal magnitude and produce equal amplitude pulses of opposite polarity with each field reversal.
2) Asymmetric mode - wherein the Wiegand Wire is exposed to field excursions which are unequal, as the name implies. The wire is first subjected to a strong field to insure the

orientation of even the outer most (and magnetically hardest) "shell" material. Next, it is exposed to a modest field of opposite polarity intended to reverse the orientation of the inner "core" material. When returned to a field of the original saturating polarity, the core will flip to realign with the shell, producing a large flux change as it does.

Of the two modes, the symmetric type has a distinct advantage over asymmetric in that a small but discernible pulse is produced with each field change and, when applied to an appropriate mechanical design, direction of motion may be indicated by the pulse polarity. The disadvantage of symmetric excitation in applications known to date is the relatively low pulse amplitude, typically ranging from .5 to .8 volts using a typical sense coil of 2,000 turns.

When pulse amplitude is critical, most designs have relied on the asymmetric mode, which yields a much larger but singular pulse per magnetic cycle, with typical amplitudes of 2 to 5 volts. While enjoying the advantage of large output pulses, asymmetric driven systems require rather tight control over the magnitude of the reversing field (on the order of ± 5 oersteds), which is difficult to hold in most mechanical designs. In many cases, redundant asymmetric systems have been used where directional indication and large pulse amplitude were both needed.

Traditionally, it has been considered proper to maximize the exposure of the Wiegand Wire to the axial or longitudinal fields. This was especially true when the magnetic circuit designs incorporated Alnico magnets, which, in their preferred Length to Diameter ratio, appear as long cylindrical shapes. As a "rule of thumb", magnets used were approximately 10% longer than the length of the Wiegand Wire. For reference purposes, any drive field length greater than that of the Wiegand Wire will hereafter be termed "Long Field".

The relatively strong demagnetizing fields that occur naturally at the cut wire ends have long been known to adversely affect wire performance in lower intensity drive fields, and are the primary reason for the strong saturating fields necessary to precondition a wire. In addition, any malady in the cutting process may grossly exaggerate these end effects at the expense of pulse amplitude and stability.

In an effort to minimize component size, enhance the output under symmetric drive, and reduce the undesirable effects of the wire ends, a new method of excitation has been developed.

The key element in this technique is the nulling (or bringing to zero) of the longitudinal magnetic drive field inboard of the ends of the wire. Termed "Short Field", this technique terminates the operational portion of the wire magnetically rather than physically.

A major advantage in the use of "Short Field" technique is that these troublesome ends may now be excluded from the operational area of the wire and therefore free the system from "end effect" related problems.

As shown in Fig. 1, where axial field intensity is plotted in relation to the Wiegand Wire length, the drive field is peaked at its center and reduced to essentially zero at approximately one magnetic domain length (.10") inboard of the cut wire end on each side.

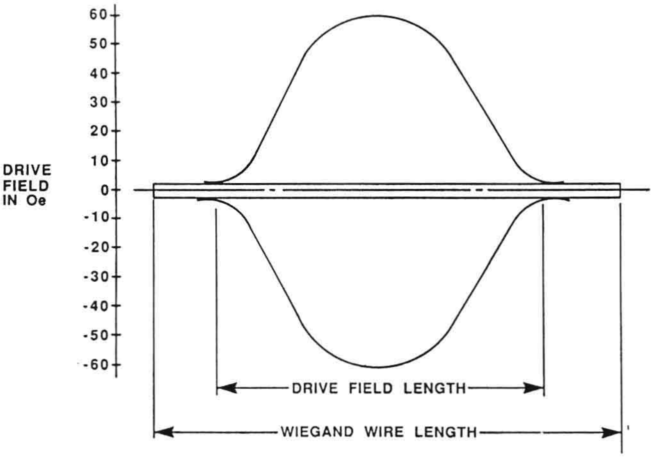

Figure 1. Drive Field vs. Wire Length Short Field Excitation

An important consideration in this new technique is the effect of strong external magnetic fields on the portions of Wiegand Wire which lie outboard of the strong magnetic excursions in the center, yet inboard of the magnetically nulled ends. Since the operating principle of the Wiegand Effect is based on a relationship between the magnetic orientation of the core and shell regions of the wire, any externally induced reorientation of these regions will have a profound impact on performance.

Also, in the interest of magnetic

efficiency, it is desirable to create a field intensity envelope as shown in Fig. 1 using as little magnet energy as is possible.

To resolve both of these problems, specially designed sintered pole pieces are used to create an eliptical field intensity profile and to shield the vulnerable areas of the wire (see Fig. 2). Since their tapering wall thickness inversely matches the lessening drive field (and inherent reorientation capacity), their ability to protect exactly matches the need. With proper design, a system with magnetic drive field excursions of as little as ± 50 oersteds can be nearly immune to the influences of external magnetic fields, while producing symmetric Wiegand pulses with amplitudes in excess of ± 2 volts.

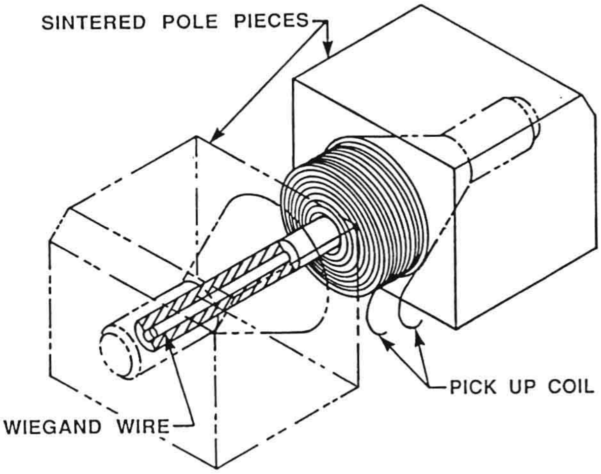

Figure 2. Wiegand Wire Using Sintered Pole Pieces

PERFORMANCE - SHORT FIELD VS. LONG FIELD

It has been stated that conventional long field symmetric drive conditions produce low amplitude pulses (one per field change), and that long field asymmetric drive produces a single, much larger pulse per cycle.

In comparison, short field techniques, while producing similar results in asymmetry, can produce symmetric output with pulse amplitudes equivalent to those of asymmetric drive.

To illustrate the difference, a Wiegand Wire and pick up coil assembly was tested in both long and short field solenoids having equal peak intensity symmetric drive fields of ±60 oe. Figure 3A and 3B are illustrations of the hysteresis loops generated during these tests.

Figure 3A shows the traditional symmetric driven loop with the most significant flux jumps appearing as discontinuities in the second and fourth quadrants as a result of reversing the polarity of core material. Other, minor flux jumps appear in quadrants one and three as a result of the reversal of shell material. The most significant pulses in this system produce an induced voltage in the 2000 turn pick up coil of approximately .8 volts.

Figure 3B shows the equivalent information for the same pick up coil and wire sample when exposed to short field drive. In this case, the much larger single flux jump which occurs with each drive field reversal produces an induced voltage pulse of approximately 3 volts.

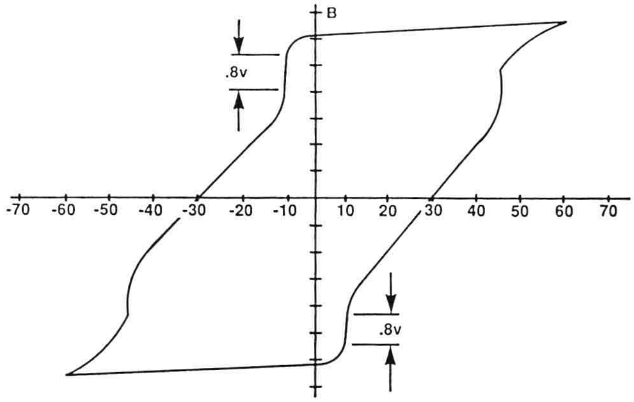

Figure 3a. Long Solenoid Symmetric Drive

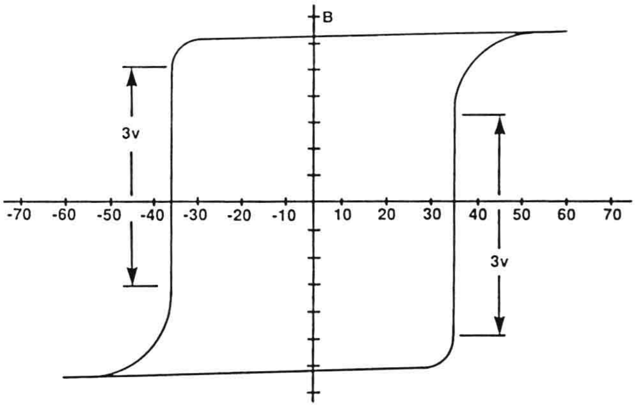

Figure 3b. Short Solenoid Symmetric Drive

DYNAMIC PERFORMANCE

A natural concern of system designers is the amount of variability in both pulse amplitude and firing point (point of pulse occurrence). In dealing with the Wiegand Effect, these characteristics must be subdivided into two categories:

1) Inherent - those variabilities caused by the micro-physics involved in the actual flux jump. Although generally minor in nature, these variabilities result in a small range of amplitudes and firing points for any given and repeatable field excursion.
2) Mechanical - the range of average pulse amplitudes and firing points in relation to drive field intensity. In application, this amounts to shifts in pulse amplitude and firing point due to variations in the magnitude of the drive field. These would be caused by changing physical conditions, such as mechanical runout on rotating members, part to part variation in actuator assemblies, etc.

Both of these conditions can be minimized to acceptable levels by proper design and configuration.

Since there are a myriad of possible configurations of magnet actuators and sensor orientations (each having unique drive field excursions and rates of change per unit of motion), the graph in fig. 4 has been developed to describe pulser performance under a

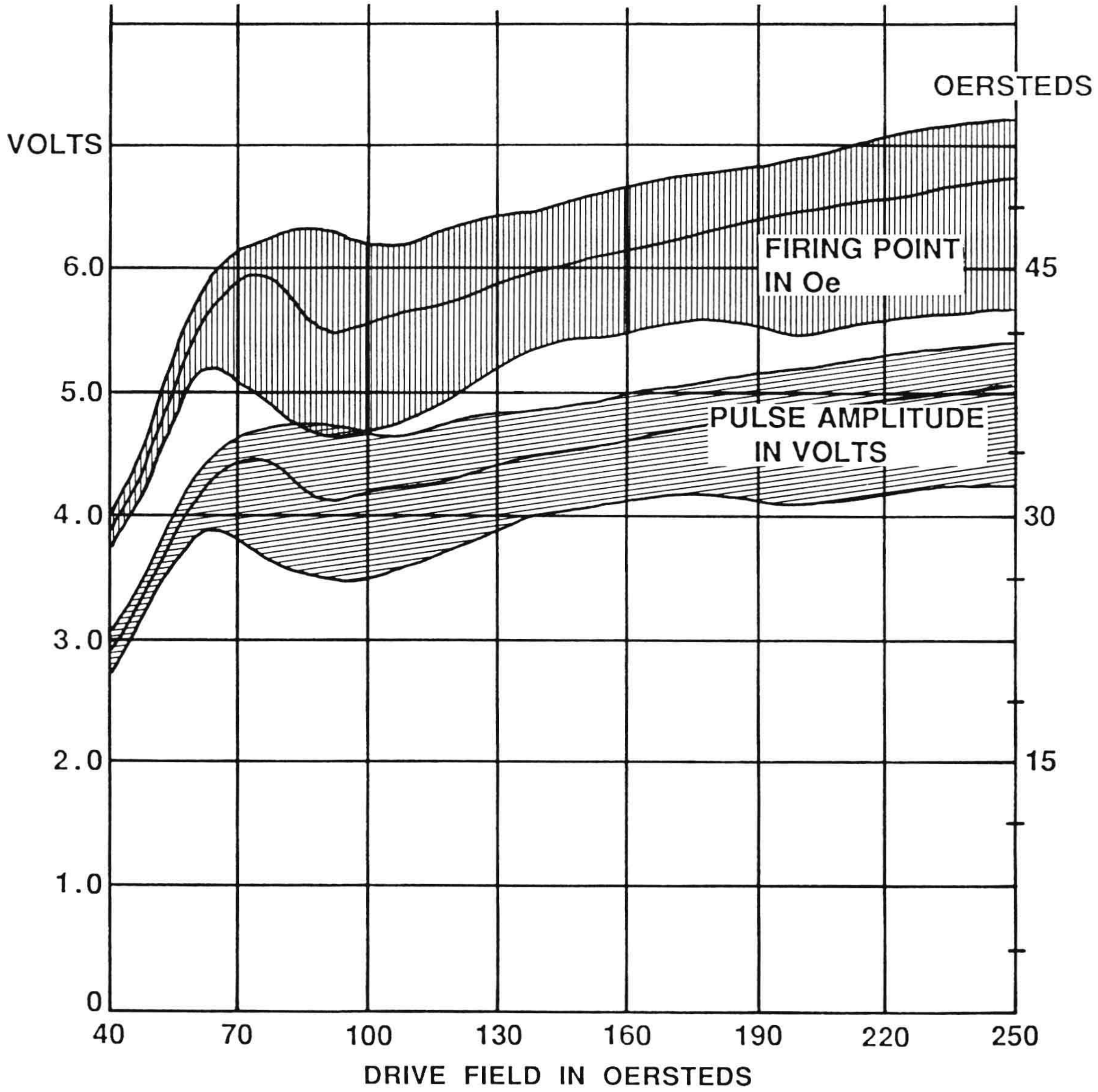

Figure 4. Firing Point / Pulse Amplitude vs. Drive Field

broad range of drive field excursions. Once a spectrum of drive field has been determined for a specific application, the expected range of firing point occurrence may be derived from fig. 4. By applying this range of firing points (in oersteds) to the rate of field change per unit of motion (at the approximate point of firing), one may determine the accuracy of the particular system in terms of motion units. (inches, degrees of rotation, etc.).

PRACTICAL APPLICATIONS

While this new technique may be applied to many pulser design concepts, one of the most popular and elegantly simple is that of magnets in motion. In this form, the pulser assembly contains only the Wiegand Wire segment, the pick up coil, and the shaped pole pieces. The changing magnetic field is supplied externally. This arrangement is most useful whenever relatively few pulses per motion cycle are required and large air gaps may be encountered. See Figure 6.

A typical pulser design for moving magnets is shown in figure #5. Item #1 is the actual Wiegand Wire segment cut to a length slightly shorter than the glass containment tube, Item #2. A pair of silicon rubber end caps, Item #3, close off the open ends of the tube to prevent any encapsulation epoxy from entering. They also provide resilient cushions for the tube ends, where they are supported in the sintered iron pole pieces, (Item #4). For applications with only modest expected operating temperatures, the glass tube and cushions may be eliminated. However, whenever extreme temperatures must be encountered, it is best to allow the Wiegand Wire to "float" in a loose fitting but rigid containment tube to avoid temperature induced stresses.

Wound on the glass tube is a pick-up coil of approximately 1,500 ohms characteristic impedance (Item #5), both ends of which connect to terminals mounted in the molded plastic base (Item #7). For environmental security, the assembly is covered with a non-magnetic stainless steel shell (Item #6) and filled with epoxy potting.

The pole pieces in this design are approximately 1/4 inch cubes of magnetic grade sintered iron, formed with conical shaped cavities. When the pole pieces are positioned as shown, these cavities establish the necessary eliptical field intensity profile, using a minimum of magnetic flux from the external magnet source.

Experiments indicate that a 30^0 taper of the conical walls and a .100" spacing between the pole pieces produces optimal results. Output pulses in excess of ± 3.0 volts may be achieved with drive fields of ± 60 oe. Of course, the actual magnet strength requirements for any system are largely dependent on air gaps to be encountered, and any local ferrous materials which may influence the magnetics.

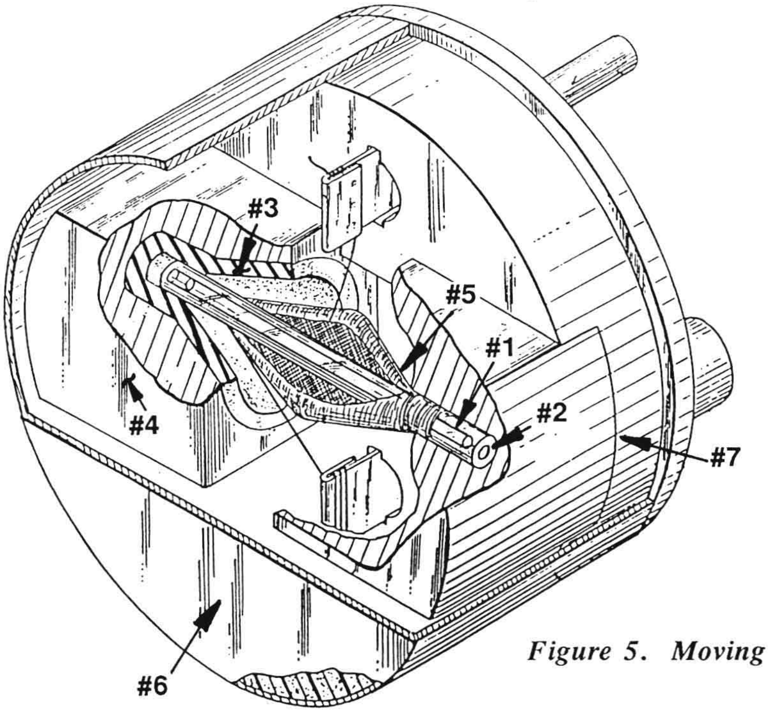

Figure 5. Moving Magnet Pulser

MAGNET CONFIGURATIONS

In order of complexity, a few of the possible magnet configurations are demonstrated in Fig. #6, with typical resultant output wave form shown in Fig. #7. Pulse amplitude is largely independent of speed and the firing point of each pulse is a function of the magnetic field developed across the air gap between the pole pieces. Although these magnetic excitation systems are physically different, each produces one Wiegand pulse per field reversal as the differential between pole pieces reaches approximately 35 oe. Referring to figures #3B and #4, care should be taken to insure that the total excursion of the field is in excess of ± 60 oe to insure reliable symmetric operation.

Working air gaps between the pulser and magnet(s) are generally limited only by the size of the magnet(s) and physical considerations. An additional advantage of the pole piece design is the ability to gather flux and concentrate it across the gap containing the Wiegand Wire. This makes the overall system extremely forgiving of air gap, misalignment, and off-angle operation.

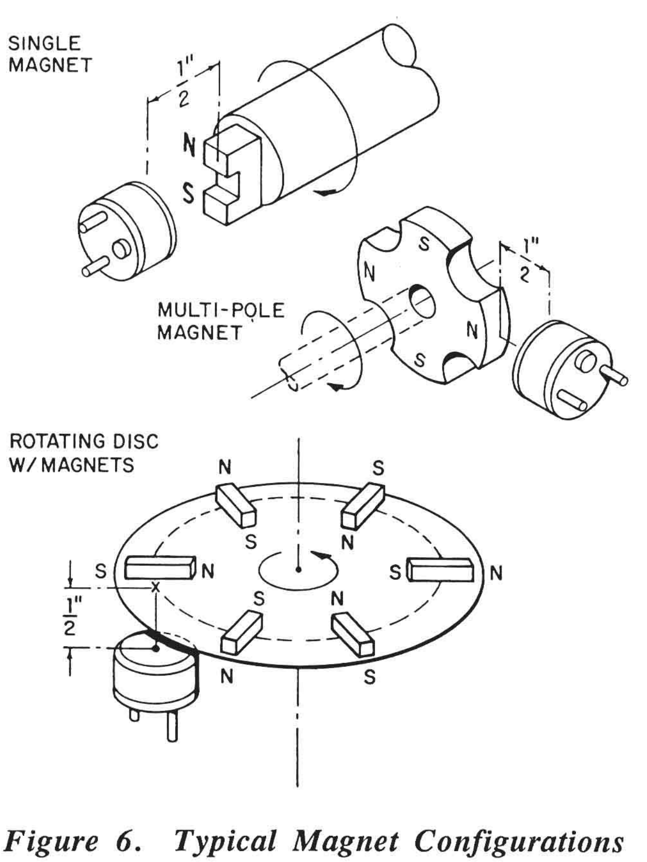

Figure 6. Typical Magnet Configurations

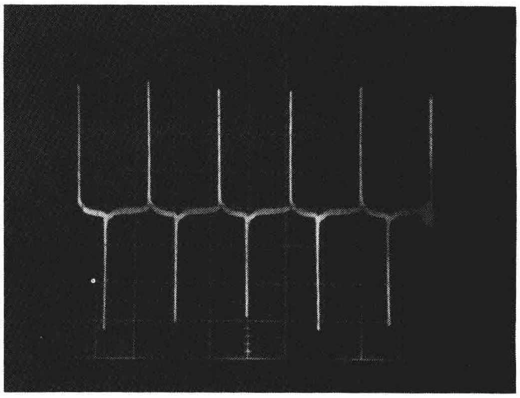

Figure 7. Waveform of Output Pulse Trai

CONCLUSION

Recent developments in application technique have ushered in a new era for pulser designs based on the Wiegand Effect. Rugged and reliable pulsers may now be produced which generate symmetric, bipolar output pulses of ± 3.0 volts and operate with large working air gaps. The inherent advantage of insensitivity to speed is now enhanced by the stabilizing effects of the pole pieces, which make the pulser most forgiving of air gap and alignment. Combined with an ability to operate in extreme temperatures, the Wiegand Effect is now an even more attractive technology for sensing motion or proximity in harsh environments, especially when low speeds are to be encountered.

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880407

Non-Contacting Sensors for Automotive Applications

Roger F. Wells
Spectrol Electronics
Subsidiary of United Technologies, Control Systems

ABSTRACT

The current trend in automobile design is for more sophisticated electronic controls for systems which include power train, suspension and steering. This necessarily increases the need for low-cost reliable sensors to measure the various parameters of speed, position, torque etc. Sensors currently used often employ contacting elements to translate these measurements into electrical analogs. These devices inevitably wear and suffer loss of performance in service. There is, therefore, a need for a new generation of non-contacting devices which will not wear out within the anticipated lifetimes of motor vehicles.

This paper describes some of the technologies presently available for non-contacting sensors and discusses some of their advantages and disadvantages. Also described are improved performances of conventional contacting sensors which should always be considered before opting for the more expensive technologically advanced devices.

MANY PAPERS AND ARTICLES have been written which predict the very rapid growth of sensors in automobiles. These predictions have certainly materialized and growth shows very little sign of tapering off. Pre-1940's cars were equipped with rudimentary sensors for measuring the primary health functions of the vehicle i.e., oil pressure and water temperature, also indicators such as road speed and fuel level. As in modern cars, they provided the controlling computer with information necessary for the safe and comfortable operation of the vehicle, except that then the controlling computer was the driver. The driver also fulfilled the functions of many sensors by hearing knocks, smelling a hot, oily engine, feeling uncomfortable vibrations and intuitively knowing when the power output was low.

The ubiquitous microprocessor has now taken over many of the non-driving decisions of the person behind the wheel and eliminated most of the undesirable characteristics of the "infernal" combustion engine. These computers seem nothing less than miraculous to those of us who remember the spitting and coughing of cold gasoline engines when the accelerator was pressed too far, or the rattling and knocking which occurred when economic necessity made us use the cheapest gasoline. Who can fail to marvel at a modern motor car which will smoothly accelerate from a standing cold start with ne'er so much as a stutter? This major improvement is just as much attributable to sensors as it is to the computers.

The large degree of electronic sophistication has brought with it a need for levels of reliability which are several orders of magnitude greater than for the non-electronically controlled cars. From a nostalgic viewpoint, it seems rather glamorous to have had mystical tricks to fix the numerous recurring problems, but remember back to the fingers badly burned by juggling red hot sparking plugs which had been placed on the stove when trying to start a cold, flooded engine, and you will begin to understand the very high degree of reliability which we all take for granted. This reliability is a major concern for all automotive engineers as sensors in particular must function correctly under all conditions. A major sensor malfunction will, at best, cause the computer to select "limp home" mode. The accompanying flashing dashboard sign advising the motorist to "immediately have the engine serviced" causes a feeling of dread as it invariably heralds a very large repair bill.

With the goal of producing components which will function perfectly for the entire life of a car, non-contacting sensors for measuring parameters of moving parts are very high on the automotive engineer's wish list. After all, if nothing is touching, then it can't wear out, can it?

This paper discusses some of the techniques which are being used or considered for non-contacting sensors, but, as will become clear, the search for the perfect sensor is often frustrated by cost, environmental and manufacturing difficulties.

PRIOR ART

Before dealing with the non-contacting technologies, it is worthwhile to consider the potentiometric sensors which are still being used extensively. Throttle position, exhaust gas recirculation (EGR) valve position, and fuel tank contents are currently being measured with potentiometers. The first two applications use conductive plastic elements while fuel measurement is by wire-wound resistors or cermet type resistive inks. The evolution of these types of sensors has resulted in quite remarkable improvement in reliability and life. Figure 1 shows an EGR position sensor which has a conductive plastic element. Its tested life at 100 deg C exceeds 1 billion dither and 3 million full strokes.

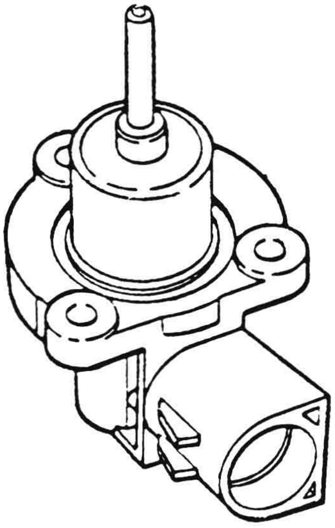

Figure 1. EGR Sensor

Figure 2 shows the life test graph for a typical EGR sensor. The test conditions were 0.026 inches movement, 60 Hz frequency and 100 deg C ambient temperature. The dither region is indicated on this graph and it can be seen that although a slight disturbance is evident, the device is still well within the +/- 1% linearity band.

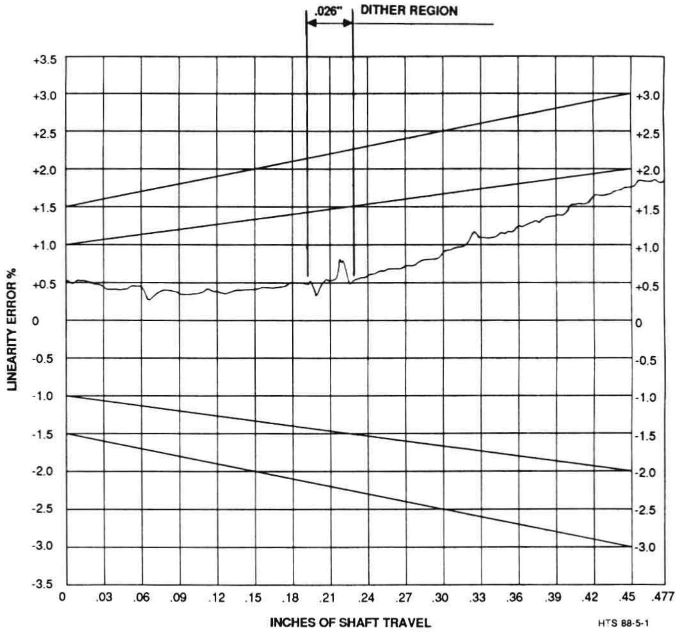

Figure 2. Life Test Curve for EGR Sensor

The dither life curve given at Figure 3, shows a fall-off in performance at elevated temperatures, but for applications such as accelerator pedal position, where the driver most assuredly will not be at all happy with his feet in 120 deg C ambient air, conventional sensors should be considered for their low cost and simple electrical interfacing.

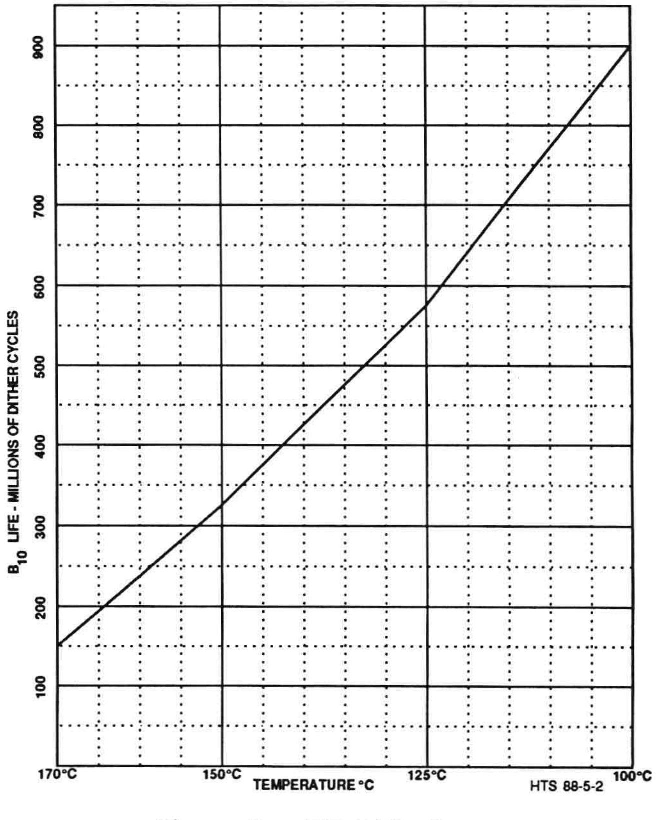

Figure 3. B10 Life Curve

Typical performance characteristics for conductive plastic potentiometric sensors are:

Temperature - -40 to +150 deg C
Absolute linearity - 1%
Microlinearity - 0.1%
Hysteresis - 0.25%

MEASUREMENT OF ROTATIONAL SPEEDS

Automobile manufacturers have been using non-contacting speed sensors in virtually all applications since the mechanically driven speedometers and tachometers were replaced by their electronic equivalents. The presently used sensors should strictly be described as pulse generators where the pulse frequency is directly proportional to the speed of the rotating member. Several different principles are used, each having their own merits and disadvantages. The three main categories of speed sensors are optical, self generating and electronic. Optical sensors, while having extremely good low and high speed capability, are rarely used in automobiles because of the inherently dirty environment and, therefore, are not discussed here.

SELF GENERATING SENSORS

Reed Switch - While this device does not actually generate an electrical pulse, neither does it require external power to produce a switch closure. It is, therefore, included in this category. Two different configurations are used. Each type has a rotor in close proximity to a reed switch. In one, the operating magnets, which are part of the rotor, open and close the switch as each pole passes. The other uses a single fixed magnet situated close to the reed switch. A slotted wheel alternately blocks and uncovers the magnetic pathway, thus producing a pulse train of switch closures. Because the reed switch is a mechanical device, contact bounce limits it to a practical upper frequency output of 600 hz. In addition to the speed limitation, the time to open and close the contacts results in a phase shift error between the passing of the actuating tooth and the actual contact closure. The phase shift error obviously increases with speed.

Variable Reluctance - In its simplest form this device is an ac generator with configurations very similar to those of the reed switch sensors. The most common construction is a combined coil and a magnet which is placed very close to a rotating ferromagnetic toothed wheel. The moving teeth change the magnetic flux in the vicinity of the coil and pulses of electrical current are induced. The second method uses a rotating magnet close to the coil. In either case the output is approximately sinusiodal, with an amplitude proportional to the peripheral speed of the rotating element, and is expressed by:

$$V \text{ output} = d\Phi/dt.$$

The output voltage is, therefore, a function of the rotational speed. The main advantages of the variable reluctance sensor are its simplicity and low cost. Its output, however, decreases in magnitude as the rotational speed becomes slower until a situation occurs when the signal cannot be separated from background electrical noise. This sensor is not very suitable for low speed applications or those where significant electromagnetic noise is present. Unless the coil and magnet are well constrained or encapsulated, mechanical vibration can also generate unwanted signals from the relative movements of these components. One further disadvantage is that the raw output usually requires some form of signal conditioning to convert it from a varying magnitude sine wave equispaced about a zero axis to a positive or negative square wave with constant amplitude.

Wiegand Effect - This is a phenomenon which occurs in a magnetically bistable conductor. A coaxial wire is constructed from two different ferromagnetic materials, each respectively exhibiting high and low coercivity. Under the effects of a strong magnetic field, both components of the wire are magnetized to their respective saturation levels. When the magnetic field is gradually reversed, the softer element readily changes its polarity while the other maintains its original polarization to much larger field intensities. At a certain reversed field strength, the hard element suddenly switches to the new polarity and the resulting magnetic pulse, of approximately 20 to 50 microseconds duration, is used to induce a voltage up to 5 volts in an adjacent coil. Speed sensors are usually constructed with a coil wound around the Wiegand element. The magnetic field variation is provided by several magnets mounted on a rotating disc. The magnets are mounted such that N and S poles alternate as each magnet passes the sensor. The output level from Wiegand sensors is independent of speed and, as shown in Figure 4, is of near constant amplitude.

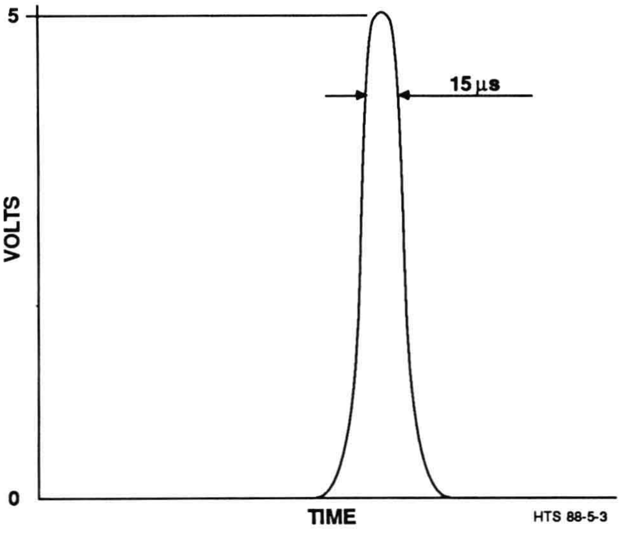

Figure 4. Voltage Pulse from a Wiegand Device

ELECTRONIC SENSORS

Variable Reluctance Sensors with dc and ac Excitation - These sensor types are similar in construction to the previously described variable reluctance sensor. The dc excited sensor uses a simple electromagnet to provide the necessary field strength. Its main advantage is, that by controlling the field current, the output can be limited to a reasonable value whereas the permanent magnet device has outputs which can easily exceed 100 volts. AC excitation gives the ability to improve the resolution and also to use the sensor down to zero speed. Both of these devices need external excitation and output signal conditioning.

Hall Effect - This is becoming an increasingly popular type of sensor and is often used for low speed applications where the variable reluctance sensor is not particularly suitable. Its elemental component is a rectangular semiconductor which, when subjected to a magnetic field, produces a voltage at right angles to an applied current flow. This "hall" voltage is proportional to the intensity of the field. This type of sensor is often used as a proximity device where the hall voltage is a function of the distance between sensor and target. When being used as a speed sensor, its basic construction is similar to the variable reluctance sensor with a fixed biasing magnet. The change in flux caused by the teeth of a rotating ferromagnetic toothed wheel alters the hall voltage. Because hall voltages are very small, the output signal must be amplified and conditioned to produce a suitable square wave. Hall effect sensors are manufactured either with a flat end to sense the passing of a wide tooth such as that of a straight cut gearwheel or with a slot through which is passed a ferrous notched vane. Some common problems encountered when using a hall effect sensor are:

- The very fine wires used for the integrated circuit often break under thermal and/or mechanical stress,
- Some configurations use a capacitor in the circuit. This gives a small time lag making zero speed detection impossible,
- The presence of strong magnetic fields in the sensor's vicinity can cause errors.

Magnetoresistive - These sensors use a magnetically biased element which exhibits a resistance change in proportion to magnetic field strength. The construction and application is almost the same as the flat-ended hall effect sensor but it has several advantages viz.

- The sensing element is passive i.e., it requires no excitation voltage,
- It will operate over a very wide frequency range of zero to 5Mhz,
- Very small, fine-toothed pulse wheels can be used.

With a ferrous magnetoresistive element, the resistance change is of the order of 3% and, therefore, amplification of the output is required.

Eddy Current - This is a sensor technology not commonly used on automobiles but which offers several advantages when compared with other types of sensor. Two main types of eddy current sensors are available. The first has a flat end with a detector coil. It functions by measuring the modulation of radio frequencies (RF) in the coil caused by eddy current generation in an adjacent electrically conducting substance. The second uses a vane-type pulse wheel made of conducting material which passes between a pair of coils. The sensor generates a high frequency magnetic field which induces eddy currents in any conducting material placed near the coils. The sensor's circuitry detects the eddy currents when a conductor is present and produces a high output signal. When the sensor detects no eddy currents, i.e., a gap in the sensing wheel, a 0 volt (logical low) signal is produced. The unconditioned output from this sensor is a logical 0 to 5 volt square wave pulse. Some of the advantages offered by eddy current sensors are:

- Zero speed detection,
- Uses no magnets,
- Highly immune to RF and electromagnetic interference,
- Pulse wheel can be made from any electrically conducting material or solid non-conducting disk with conductors etched, printed or screened.

The eddy current device has several other unique qualities. In the case of the basic sensor, the rising edge of the square wave is driven by the leading edge of the interrupter vane. Figure 5 shows the waveform output of an eddy current sensor used in an adaptive braking system (ABS). The wheel had 50 teeth and the equivalent road speed was < 3 mi/h.

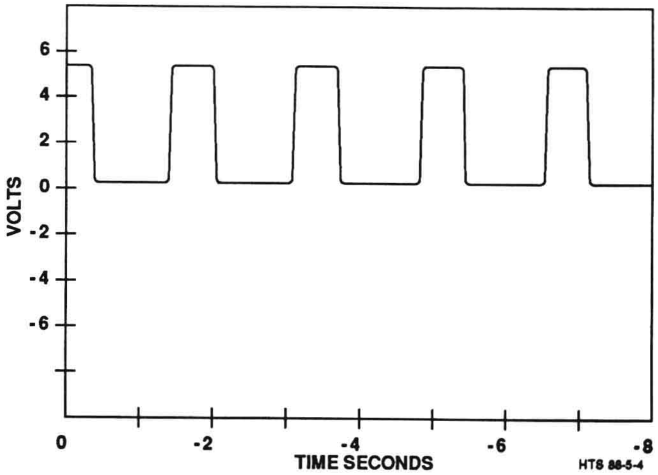

Figure 5. Eddy Current Sensor Waveform

This driven waveform output is of particular importance when the sensor is incorporated into a system which cannot accept the presence of higher harmonic frequencies. A Fourier analysis of the waveform shown in Figure 6 shows that the elemental harmonics are all less than 200 Hz.