Aftermarket Variable Reluctance Sensors

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ABSTRACT

The purpose of this paper is to enlighten the OE engineer to the work being done by their counterparts in the automotive aftermarket. Specifically, the design methodology used by the author to design variable reluctance (VR) sensors will be described.

BACKGROUND

The number of sensors in automobiles has increased to the point where aftermarket demand for replacement sensors has reached the level where distributors are demanding more complete coverage and competitive pricing. Being a major supplier of replacement parts to the automotive aftermarket, Echlin took the lead and expanded it's manufacturing capabilities for sensors to meet this demand.

MARKET CONSIDERATIONS

The biggest difference between manufacturing for an OE manufacturer and manufacturing for an aftermarket customer is the unit sales volume. Aftermarket sales of a given part number are a small fraction of OE demand. Although aftermarket demand for a given part number might be fairly low, the shear number of part numbers makes up the difference. Part consolidation is more important to aftermarket manufacturers than it is to OE manufacturers since OE volumes are usually high enough to afford them substantial price breaks. Remaining competitive, even at low production volumes, is the key to success as an aftermarket supplier.

There are certain criteria that must be met in designing a product for the aftermarket. Firstly, the product must function in the application as well, or better, than the original OE product. Secondly, the product must look, feel, taste and smell just like the OE part. This is important from a psychological standpoint for the mechanic that purchases the product to feel comfortable that he's been provided with the right part. Lastly, the design must not infringe upon any patents. If patents do apply, then a licensing agreement must be arranged with the patent assignee.

MANUFACTURING CONSIDERATIONS

VR sensor technology is similar to that of distributor magnetic pickups. Since Echlin has been manufacturing magnetic pickups for many years the manufacturing "know how" is well established.

The following goals are critical to being competitive at low volume production of many part numbers:

- design for manufacturability and processability
- purchase equipment that lends itself well to quick tooling and material change overs
- maximize the utilization of production equipment
- optimize the plant floor layout for smooth and efficient work flow
- design tooling and fixtures with ease of setup in mind
- establish quality plans that are realistic and meet the needs of the customer

DESIGN METHODOLOGY

When designing sensors for the aftermarket, the easiest and safest approach is to simply make a "carbon copy" of the part in question. Unfortunately, a carbon copy design is rarely the most cost effective design for the following reasons:

- the design may fit well with the OE supplier's equipment, but the aftermarket supplier may not own the same equipment
- the OE supplier may be obtaining volume breaks not obtainable by the aftermarket supplier
- designs for hard automation processes may not lend themselves to the flexible automation processes used in the aftermarket

To avoid the cost pitfalls of designing a carbon copy it's necessary to approach the project as if one were designing the original sensor for the first time (within the design constraints previously mentioned). Admittedly, the aftermarket designer has an advantage over the OE part designer in that the product already exists and can, therefore, be "reverse engineered".

During the first step in reverse engineering, samples of the sensor in question are measured, dissected, analyzed and all of the materials and processes involved in it's manufacture are identified. The engineer then proceeds with the following design steps:

- cost the design as it stands, but with any improvements that can be incorporated to provide a better product without significantly increasing cost
- cost a design modified to be manufacturable with existing equipment or using existing parts or components
- if there's cost savings associated with the use of new equipment, a cost benefit analysis is performed to determine payback
- operations are combined whenever possible to reduce costs
- components and materials are commonized whenever possible to reduce costs
- weigh the benefits against the risks associated with the changes identified and adopt only those changes which provide a significant benefit and/or little risk

A design failure mode and effects analysis (DFMEA) is used to assess the above mentioned risks associated with any design attributes and a process FMEA is used to assess risks associated with the sensor's manufacturing processes. The OE part is utilized as a benchmark.

In the case of VR sensor function, the old method of trial and error testing of working prototypes is both time consuming and cost prohibitive. A computer program for electromagnetic analyses was recognized as an important tool to afford design optimization as well as risk analysis using the OE design as a benchmark. Benchmarking on the computer allows for much quicker and simpler analyses since it's a comparative study and doesn't need to be precise in terms of absolute numbers on performance predictions.

COMPUTER AIDED ENGINEERING

Several electromagnetic software packages were reviewed prior to selecting MAGNETO, a 2-D planar and axisymmetric program from Integrated Engineering Software. Although there are sensors that can only be modeled with a 3-D program, 3-D modeling is much more difficult and time consuming than 2-D modeling. The great majority of VR sensors can be quickly and accurately modeled with a 2-D/axisymmetric program.

When a VR sensor is modeled it's usually the sensor's output voltage that's of primary concern. A VR sensor generates an analog voltage signal when a toothed or slotted ferrous target moves past the sensor tip. The cross section of a generic VR sensor design is shown in figure 1. Simply stated, a voltage is induced in the sensor's coil when there is a *change* in magnetic flux through the coil.

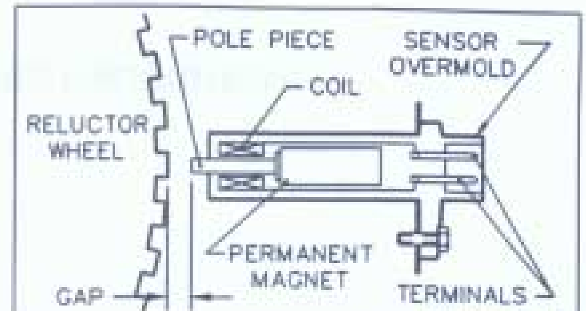

FIGURE 1

The following relationship applies:

$$V = N\left({}^{d\phi}\!/_{dt}\right)$$

where

V	= induced voltage (Volts)
N	= number of turns in coil
ϕ	= flux through coil (Webers)
t	= time (Seconds)

In the case of comparative performance we're not interested in knowing the exact signal shape, simply the signal magnitude. Therefore, …

$$V = N(\Delta\phi / \Delta t)$$

The electromagnetic program is used to determine $\Delta\phi$ max by calculating the flux through the coil in the maximum flux condition and comparing it to that of the minimum flux condition. The time to transition from maximum to minimum flux is Δt .

Often, the best way to describe an analytical procedure is to use an example. The example used in this paper will not be identified, but is a real life example of a VR sensor that was redesigned and put into production for aftermarket distribution.

ESTABLISHING A BENCHMARK

Figure 2 illustrates the cross section of the subject OE sensor. The magnet is composed of A1NiCo 5. The pole piece is machined of low carbon steel and is welded to the magnet. The coil is positioned over the pole piece as shown and is composed of 4400 turns of AWG #41 magnet wire.

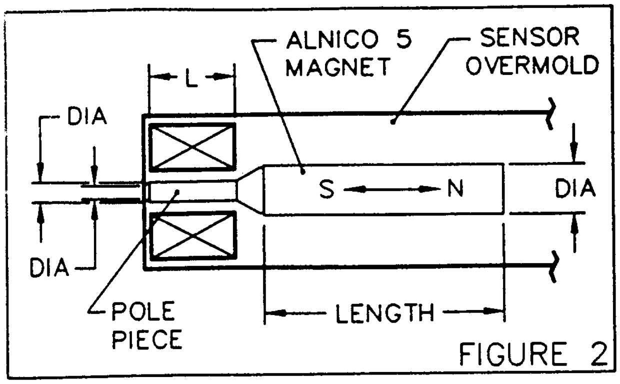

FIGURE 2

The first step in analyzing a sensor is to determine whether to use 2-D planar, axisymmetric or 3-D spatial modeling (need 3-D software) and generate the model accordingly. In this case axisymmetric modeling works best. Next it's necessary to determine how to model the various components that make up the magnetic circuit. In this example modeling is straight forward because all components are axisymmetric. If the pole piece had been square, then it would have been necessary to convert the square cross section into an equivalent circular cross section since the 2-D software cannot mix 2-D planar and axisymmetric modes.

Once the model has been established on the computer it's necessary to add the reluctor wheel to the magnetic circuit. Since we're only looking to establish a benchmark against which design alternatives can be compared, we can model the reluctor wheel as a simple disc of steel at a set gap under the tip of the pole piece in the maximum flux condition. The minimum flux condition is modeled with no steel under the pole piece – simulating a position between teeth or in the middle of a slot on the reluctor wheel. Figure 3 shows the model in the maximum flux condition.

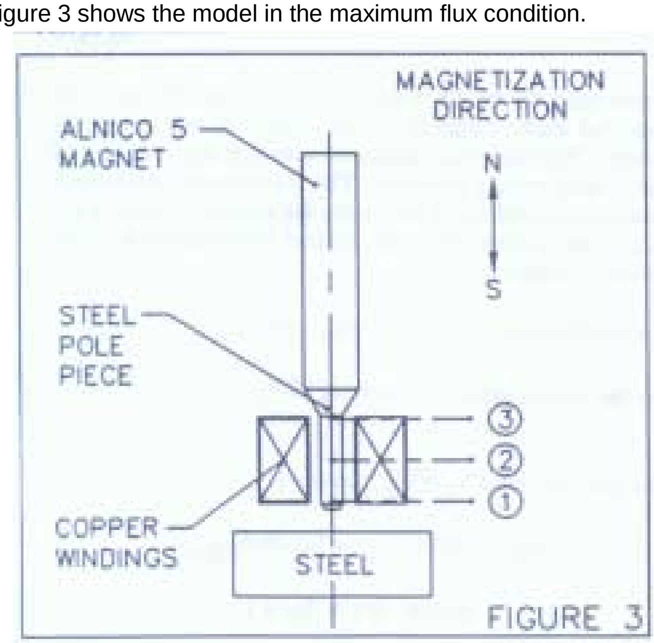

FIGURE 3

Next, the program is used to calculate the y-component of flux density, B_y (Telsa), through the coil. A figure for total flux, ϕ (Webers) is then obtained by integrating from the centerline of the sensor radially to the outside diameter of the coil. Because the flux varies along the length of the coil, an accurate solution is obtained by averaging the flux along the length of the coil. We've found that we obtain a good average by calculating flux at three points in the model – both ends of the coil and through the middle of the coil (shown as slices 1,2 and 3 in figure3). Figure 4 illustrates the distribution of flux density, B through slice 1.

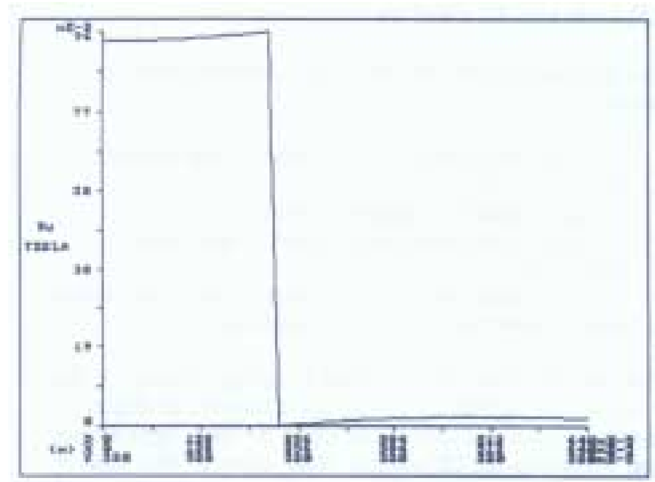

FIGURE 4

Integrating, we find that flux through this section of the coil is 14.7 X 10^{-6} Webers. Carrying this analysis to sections 2 & 3 we obtain values of 22.3 X 10^{-6} Webers and 25.6 X 10^{-6} Webers, respectively. If we plot flux against position, we obtain the graph shown in Figure 5.

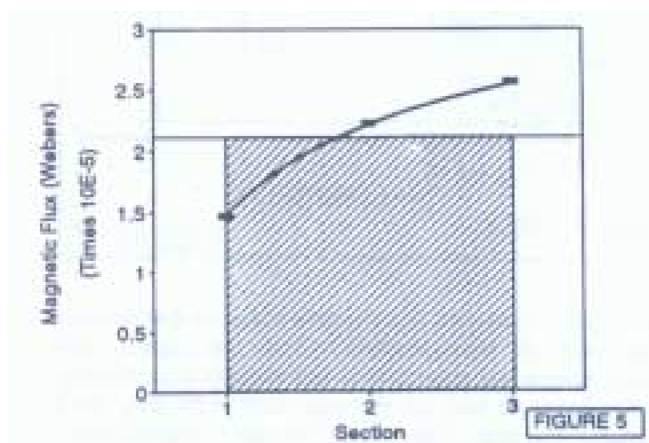

FIGURE 5

After defining a best fit curve for these three points, the curve is integrated from point 1 to point 3. Dividing the integral by the length of the coil yields the average flux through the coil. For the maximum flux condition the average flux through the coil equals 21.6 X 10^{-6} Webers.

The same analysis is repeated after modifying the model for the minimum flux condition (i.e.: remove the steel from in front of the sensor tip). We find that the average flux through the coil equals 18.2 X 10^{-6} Webers in the minimum flux condition.

$$\Delta\phi = 21.6 \times 10^{-6} - 18.2 \times 10^{-6} = 3.4 \times 10^{-6} \text{ Webers}$$

We have now established our performance benchmark.

AFTERMARKET DESIGN

This particular sensor offered several potential areas for cost reduction:

- Welding offers only slight performance improvement at significant cost.
- The large A1NiCo 5 magnet is costly.
- The shape of the pole piece is more complex than it needs to be.
- The coil length didn't coincide with our stock tape widths (coil OD gets taped prior to overmolding).

After quickly evaluating a series of design options on the computer, we settled on the design illustrated in figure 6. Each evaluation was carried out using the same approach we used to evaluate the OE sensor. Note, however, that some of the analytical trials were abbreviated once it was discerned that the design was not a viable option.

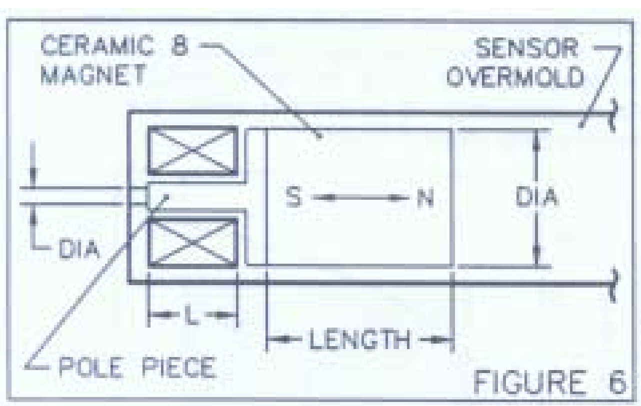

FIGURE 6

In our design the magnet is a Ceramic 8 magnet that we were already using in other products. Note that although the Ceramic magnet has considerably less strength than A1NiCo, it is the *change* in flux, not the *magnitude* of the flux, that's important. The cost of the ceramic magnet is approximately one fifth that of the A1NiCo magnet used in the OE design.

The machined low carbon steel pole piece simply lies flat against the face of the magnet, thus eliminating the costly welding operation. The geometry of the pole piece has been simplified to provide a cost savings without significantly affecting performance. The length of the coil was reduced slightly to commonize on tape with only a slight performance penalty.

Results of the analysis follow:

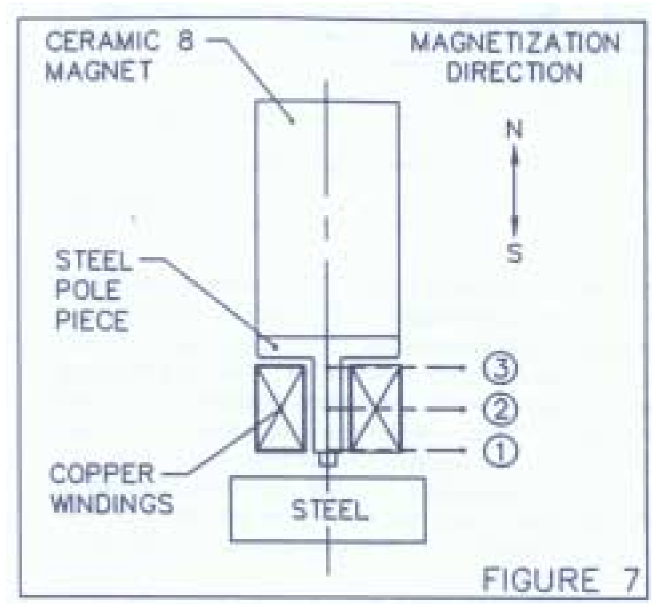

FIGURE 7

DESIGN	MAXIMUM FLUX	MINIMUM FLUX	MAX $\Delta\phi$
OE	21.6 X 10^{-6}	18.2 X 10^{-6}	3.4 x 10^{-6}
Redesign	14.9 x 10^{-6}	11.8 X 10^{-6}	3.1 X 10^{-6}

TABLE 1

Based upon the results of the analyses, we would expect the modified sensor design to perform almost as well as the OE design. This fact was confirmed with a preliminary test of the concept using a prototype. The reduction in performance was compensated for by increasing the number of turns in the coil. The number of turns required was estimated in the following manner:

For the OE sensor … $V_1 = N_1(\Delta\phi_1 / \Delta t_1)$

For the revised sensor … $V_2 = N_2(\Delta\phi_2 / \Delta t_2)$

Our goal is to have $V_1 = V_2$, therefore …

Set $N_1(\Delta\phi_1/\Delta t_1) = N_2(\Delta\phi_2/\Delta t_2)$

And set $\Delta t_1 = \Delta t_2 = 1$

Solving for N_2 we obtain …

$$N_2 = N_1(\Delta\phi_1/\Delta\phi_2)$$

N_2 = 4400 (3.4 / 3.1) = 4826 turns

The only problem with adding turns to the coil is that the sensor resistance will increase. As long as the resistance stays within the range published in the OE service manual, then we feel comfortable that the higher resistance will not cause confusion in the field. The added cost for an additional 400 turns on the bobbin was far outweighed by the savings associated with our design.

In terms of analytical performance versus actual tested performance, Table 2 summarizes the data and tabulates the resulting error. These measurements were obtained by spinning a standardized test reluctor wheel at 150 rpm and matching the air gap to that of the theoretical studies. The predicted voltages were calculated by using the OE sensor as a benchmark to solve for Δt which becomes a constant, holding all else constant.

DESIGN	PREDICTED VOLTAGE	MEASURED VOLTAGE	ERROR
OE Design	DATUM	2.80 V	DATUM
Redesign (N=4400)	2.55 V	2.48 V	2.7%
Redesign (N=4800)	2.79 V	2.69 V	3.6%

TABLE 2

CONCLUSIONS

Aftermarket engineers approach the design process in a manner that is different, in many ways, to the approach used by OE engineers. Reverse engineering procedures are utilized to define a design that meets the demands of the application and remains cost competitive even at low production volumes.

An electromagnetics computer program is an important tool for optimizing and cost reducing variable reluctance sensor designs as well as reducing their time-to-market. Two dimension and axisymmetric finite element or boundary element analytical computer programs offer very quick modeling and analyses without sacrificing much accuracy over more time consuming 3-D programs when applied to a majority of VR sensor designs.

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2. Magnetic Materials Producers Association, *Permanent Magnet Guidelines*, Supplement PMG-88 to MMPA Std. No. 0100, 1988.