ROBUST MAGNETICS DESIGN - A CASE STUDY

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ABSTRACT

Quality products are those which consistently meet customer expectations. Typically consistency is achieved by exercising tighter control over the manufacturing process that produces the product. However, this strategy eventually becomes impractical for either technical or cost related reasons. Instead of attempting to exert tighter control over the manufacturing process, it may be preferrable to redesign the product so that its performance is less affected by the inherent variation of its manufacturing process. So-called, robust designs are often the cost-effective way to achieve product consistency.

BACKGROUND

In 1989, Motorola Inc. decided to enter the electronic ballast market, and a wholly owned subsiderary, Motorola Lighting, Inc., was created. In addition to being dedicated to producing the best electronic ballast in the world, Motorola Lighting was equally determined to implement quality oriented operating concepts. One of these concepts is the development of supplier partnerships. Ferrite International was selected to be Motorola Lighting's supplier of the ferrite cores that would be used in the magnetic components of the electronic ballast.

The consistency of the performance of the final product is influenced by its design, its manufacture, and its component parts. Because of this supplier partnerships are an integral part of any total quality management program. Components can be designed and specified so that they can be economically produced and assure the performance of the final product only through mutual efforts of a supplier and its customer.

This paper describes a situation where the joint involvement of Motorola Lighting and its supplier, Ferrite International, resulted in a win-win solution to a problem that resulted in improved product performance without any increase in product cost.

DESCRIPTION OF THE PROBLEM

Consistent product performance is a keystone to Motorola Lighting's concept of Six Sigma quality. The objective of Six Sigma quality is to economically produce electronic ballasts that perform as uniformly as possible. Product performance is determined by measuring the important operating parameters of the ballast, those characteristics that determine whether the unit meets the customers' expectations. Some of the ballast performance parameters are, in part, influenced by the performance consistency of the ballast's magnetic components. In turn, the consistency of these components is affected by the consistency of the ferrite core that is used.

As part of the magnetics manufacturing process, assembled units are routinely evaluated. One of the key parameters is the component inductance. Before the inception of this project, the data indicated that the variation in the inductance of the base drive was too large if the required ballast performance consistency was to be achieved.

Since core inductance is the dominant factor affecting the component performance a problem solving team consisting of personnel from both Motorola Lighting and Ferrite International was formed to find a way to improve the consistency of the base drive's inductance.

STATISTICAL INVESTIGATION

The team developed a cause-and-effect diagram that itemized the possible causes of core inductance variation. The most likely causes were associated with the core configuration and core material permeability. Permeability was quickly ruled out as a cause of inductance variation since manufacturing records indicated the composition had not been changed during the period in question.

The focus of the study then shifted to the core configuration and the core grinding operation. Several potentially influential aspects of the core configuration were identified: leg length, gap depth, and uniformity of the gap surface, which will be referred to as flatness. The effects of each of these geometric characteristics would have to be studied before deciding on the best solution to propose.

Measurements of several manufacturing lots were made. Small samples of cores were selected periodically throughout several manufacturing runs. Each core was carefully measured, and its leg length, gap depth, and flatness was recorded. Leg lengths were measured with a micrometer. The other characteristics were determined by taking multiple measurements over the gap surface. The average of these measurements was used to characterize the gap depth, and the difference between the extreme individual readings was called the gap "flatness."

The cores were then assembled in pairs and the inductance was measured. Figure 1 shows the expected exponential relationship between the gap of the paired cores and their inductance measurement. After converting both measurements to a logarithmic scale, Figure 2, an empirical linear relationship was developed using the least squares regression technique. The resulting equation,

$$\ln \text{ind} = 4.531 - 0.837 (\ln \text{gap depth}),$$

had a squared multiple correlation coefficient of 0.998 whch indicates that 99.8%, or virtually all, of the variation in the inductance can be attributed to the differences in the gap depth.

To investigate any other effects of core configuration on inductance, the data were further analyzed using a statistical technique known as multiple linear regression. Using this procedure, the relationships between measured inductance and the three geometric characteristics were simultaneously evaluated. A total of 112 paired cores were used in this analysis.

The variations in leg length and flatness did not have a statistically significant effect on the variation in measured inductance. It is important to note that the variations in the leg length and flatness of the cores that were sampled from the production runs were relatively small. For example, leg length varied only +/- 0.0025" from nominal and the lack of flatness averaged only 0.0006." We believe the reason that the leg length and flatness were not related to the inductance variation is because the variation in these characteristics was quite small. If differences had been more extreme, we anticipate they would have caused inductance to vary.

PROBLEM SOLUTION

Clearly, inductance variation was dominated by the gap depth and any significant reduction in inductance variability would have to be achieved by controlling gap depth in some fashion. Improving control of leg length or flatness was impractical since both of these characteristics were already quite consistent.

The obvious solution was to use a core with a larger gap depth. The exponential relationship between gap depth and inductance translates into less sensitivity in inductance to changes in gap depth as the gap depth increases. However, the only way that a larger gap depth could have been used without altering the nominal inductance value would have been to use a larger core. The increased thickness of a larger core would have increased the cross sectional area and, therefore, required a larger gap. Because of increases in circuit board footprint requirements, weight, and cost that alternative was ruled out.

Instead, we elected to use a set of core with only one side being gapped. When a two-sided pair is used, the gap depth of each half is subject to manufacturing variation. The resulting tolerance build-up can be calculated by

$$\sigma_{\text{total}} = \sqrt{(\sigma^2_{\text{side1}} + \sigma^2_{\text{side2}})} = \sqrt{2}\,\sigma.$$

This means that a two-sided gapped core has $\sqrt{2}$, or about 1.4, times the variation of a one-sided gapped core. Or looking at it the other way, a one-sided gapped core has about 70% of the variation as a two-sided core. For small gap depths, such as those involved in this particular situation, the decrease in gap depth variation translates directly into a reduction in core inductance variation. For example, assume a situation where the nominal gap depth is 0.125" and the inherent manufacturing variation is +/- 0.007". Table 1 shows the decrease in inductance variation that results after changing to a one-sided gap. The range of expected inductance values is reduced from 489μH for the two-sided situation to 339μH for the one-sided gapped pair - a 69% decrease.

IMPLEMENTATION

Before implementing the design change, a trial lot one-sided gapped sets was produced at Ferrite and sent to Motorola Lighting for evaluation. The core inductances had already been measured at Ferrite before shipment, and the expected reduction in variability had been confirmed. However after the cores were assembled, a secondary problem was identified. The base drive has two windings, and a small, but meaningful, difference between the two inductance measurements was observed. This imbalance was traced to the failure of the gap to be exactly centered which, in turn, was related to the leg lengths of the two cores. The core leg lengths were then modified to center the gap. The legs of the ungapped core half were ground shorter, and the legs of the gapped core half were ground longer. This created the required gap dimension being centered when the two halves were assembled.

Even though the variation in leg length was too small to significantly influence the inductance of an individual core set, it apparently was large enough to systematically affect the difference between readings for the two windings. The data were re-examined to study the consistency of grinding process over time. The analysis indicated that, even though the leg length were well within specification, the grinding operation was not always operating in a state of statistical control. Figure 3 is a portion of a control chart analysis of the leg length parameter during the time the investigation was conducted. The x-bar chart shows there were changes in the leg length over time, and the range chart indicates the short term variation in leg length is small. Further analysis of the data revealed the shifts in leg length occurred at product change over. Improved set-up procedures were developed so that the leg lengths were consistently closer to the target value.

The discovery that the grinding process could change over time led to the implementation of statistical process control of the three core dimensions. Periodically a small sample is selected, and the gap depth, leg length, and flatness of each piece is measured. The results are plotted on x-bar and range charts. Process adjustments are made if the data indicate the process has drifted from its intended setting.

CONCLUSION

There are three lessons to be gained from this case study. First, team problem solving using statistical methods is a practical way to solve problems. Secondly, it may be possible to alter the design so that the product performance is more consistent, an important aspect of Motorola's Six Sigma quality philosophy. In this situation, redesigning to use a one-sided gapped core reduced inductance variation without increasing its cost. Finally, cooperative efforts between supplier and customers are frequently the key to finding and implementing the innovative solutions to quality-related problems.

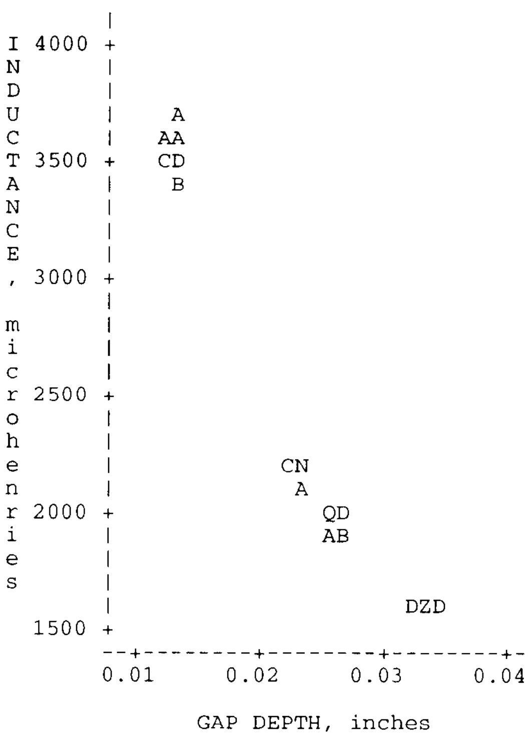

FIGURE 1
Ferrite International Grinding Study
Gap Depth vs. Core Inductance

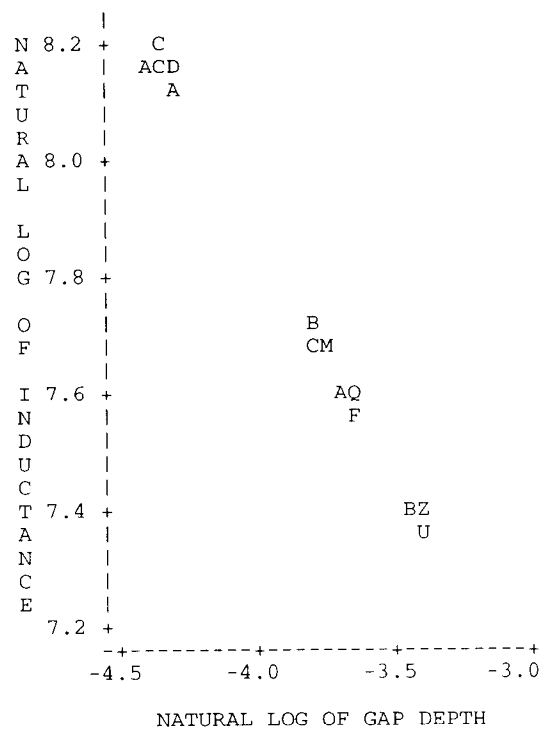

FIGURE 2
Ferrite International Grinding Study
Gap Depth vs. Core Inductance, Log Scale

```
          -----------------------------------------------------
         |11-05                                          |11-14|
          -----------------------------------------------------  3 Sigma Limits:
          -----------------------------------------------------
    .522 +                                                     |
         |                        *   *       *                |
         |                *   *           *       *   *        |
         |                                                     |
    .521 +                                                     |
 L       |                                                     |
 E       |              =====                                  |
 G       |===============   ===================================| UCL
     .52 +                                                    *| =
 L       |-----------------------------------------------------| X = .5198
 E       |                                                     |
 N       |================================================*====| LCL
 G  .519 +                                                     |
 T       |                                                     |
 H       |                                                     |
         |        *   *                                        |
    .518 +*   *                                                |
         |                                                     |
         |                                                     |
         |                                                     |
    .517 +                                                     |
          +---+---+---+---+---+---+---+---+---+---+---+---+---+
          -----------------------------------------------------
    .003 +                                                     |
         |                                                     |
   .0025 +                                                     |
         |                                                     |
 R  .002 +===============   ==================================*| UCL
 a       |              =====                                  |
 n .0015 +                                                     |
 g       |                                                     | -
 e  .001 +---------------   ----------------------*-------*----| R
         |              -----                                  |
   .0005 +*       *   *   *       *   *       *                |
         |                                                     |
       0 +====*===============*===========*===========*========| LCL
          +---+---+---+---+---+---+---+---+---+---+---+---+---+
        14:45   15:15   15:30   16:00   16:30   17:30   06:30

                          Subgroup Index (TIME)

Subgroup Sizes:   Min n=4   Max n=6
```

FIGURE 3
Ferrite International Grinding Study
Control Chart Analysis of Leg Length

Table 1
Calculated Effect of Gap Depth Variation on Core Inductance

Manufacturing Condition	Gap, inch	Gap, nat log	Inductance, nat log	Inductance, μH
Low extreme, two-sided	0.0135	-4.305	8.134	3408
Low extreme, one-sided	0.0132	-4.328	8.154	3477
Nominal	0.0125	-4.382	8.199	3637
High extreme, one-sided	0.0118	-4.440	8.247	3816
High extreme, two-sided	0.0115	-4.465	8.268	3897