APPLICATION OF TAGUCHI METHODOLOGY FOR OPTIMIZING
TEST PARAMETERS IN MAGNETO-OPTIC IMAGING

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ABSTRACT. The optimization of experimental parameters in an NDE test is extremely crucial making accept/reject decision about a test sample. For instance, in magneto-optic imaging (MOI) defects are displayed as an analog video image that is interpreted by the inspector. Subtle images such as for small surface and subsurface defects may be difficult for the inspector to detect. Under these circumstances, digital image processing methods may assist the inspector to interpret the MOI images. The accept / reject decision for a test specimen is determined by observing the binary image obtained by thresholding the magnetic flux density distribution. The coefficient of skewness of the binary magneto-optic (MO) image can be used for calculating the probability that the image contains a crack. The larger the skewness value, implies a larger likelihood of the presence of a crack. Several test parameters affect the skewness of binary MO image and hence the likelihood of the image containing a crack. The optimal set of test parameters (frequency, threshold, etc.) that generates the maximum skewness of binary image can be found using an optimization algorithm based on the Taguchi method. The number of trials necessary for the optimization is significantly reduced with Taguchi’s methodology of experimental design.

INTRODUCTION

The Taguchi method is a statistical analysis technique that is used in quality improvement and design of experiments. Dr. Genichi Taguchi simplified the conventional statistical tools by identifying a set of stringent guidelines for experiment layout and analysis of results. The approach ensures quality by optimizing the design of product/process and making the design insensitive to influence of uncontrollable factors (robustness) [1]. The method is especially suitable for engineers who do not possess sophisticated statistical knowledge.

The most important feature of Taguchi’s philosophy of quality improvement is its definition of loss function. Conventionally, a product is functionally acceptable if the measure of performance characteristic is within the allowable range. The loss function in Taguchi method is, however, defined as a quadratic function of the deviation of performance measure from its target value, as shown in Figure 1. So the basic idea underlying Taguchi’s philosophy of quality control is the minimization of variation around the target value.
To minimize the number of experiments that need to be performed without losing much information, Taguchi constructed a set of tables known as orthogonal arrays (OA), in which all interactions of order greater than 2 are neglected [2]. The use of orthogonal arrays makes the design of experiments easy and consistent. Two orthogonal arrays are employed in the experimental design using Taguchi method: inner array and outer array, which handle the controllable and uncontrollable factors respectively. Controllable factors are the parameters that can be easily controlled under practical conditions. Uncontrollable factors, also referred to as noise factors, are difficult to control in practical operations; but they are under control in laboratory conditions. For each combination of controllable factors, experiments/simulations are performed across all the combinations of noise factors. The signal to noise ratio for each set of parameters is then calculated and used in analysis to determine the optimal set of parameters.

The Taguchi approach involves (i) selecting the performance characteristics to be optimized, (ii) listing the controllable and uncontrollable factors and the levels of each factor that need to be considered, (iii) designing the experiment, (iv) conducting the experiment, (v) analyzing the results, and (vi) determining the optimal set of parameters and influence of each parameter on performance.

In this paper, we apply the Taguchi method to Magneto-optic inspection method. The simulations are performed to validate the feasibility of using the Taguchi method for optimizing simple experimental parameters such as frequency and threshold.

**MAGNETO-OPTIC IMAGING**

Magneto-optic Imaging is a relatively new non-destructive evaluation technique of detecting subsurface cracks and corrosions in aircraft skin structures. A schematic figure of the MOI system is shown in Figure 2. The magneto-optic sensor used in the MO instrument consists of a garnet film that has a magnetic anisotropy property with an “easy” axis of magnetization (very sensitive to magnetic field) normal to the sensor surface and a “hard” axis of the magnetization (insensitive to magnetic field) in the plane of the sensor.
An induction foil carrying alternating current is used to induce eddy current into the test specimen. Anomalies in the specimen, such as fasteners and cracks, generate a magnetic field component normal to the specimen and sensor surface. An easy-to-interpret and real-time binary-valued image reflecting the anomalies of the magnetic fields is then generated. Details of the principles of the magneto-optic inspection method can be found in [3, 4, 5].

The performance of an MOI system under given measurement conditions, can be evaluated using the concept of skewness to quantify the strength of the field/flaw interaction represented in the binary MO image. The larger the skewness value, implies a larger likelihood of the presence of a crack. Several test parameters affect the skewness of binary MO image and hence the detectability of flaws. In this experiment, we try to optimize the test parameters simultaneously in detecting a buried crack in the third layer of aluminum plates, as shown in Figure 3 (a). A typical crack has height 1mm, width 0.1mm and length 5mm. A 3-D finite element model [6, 7, 8] is utilized to predict the binary MO image for a given test condition. Figure 3 (b) is the predicted image corresponding to the geometry of Figure 3 (a).

Parametric studies on the performance of MOI system are usually conducted to seek the optimum value of a particular test parameter while keeping other parameters fixed. The Taguchi method, on the other hand, changes parameter values simultaneously to look for the optimum set of test parameters. Ideally, one would like to have maximum skewness. At the same time, the performance of MOI is expected to be robust under variations of the parameters. The Taguchi method provides an optimal tradeoff by conducting a signal to noise ratio analysis. The number of trials necessary for the optimization is significantly reduced with Taguchi’s methodology of experimental design.

EXPERIMENT DESIGN AND SIMULATION

The performance characteristic in this study is chosen to be the coefficient of skewness (CS) of the binary MO image. The larger the coefficient of skewness associated with a critical flaw the better the performance of the MOI system. The standard definition of CS is the third moment of the experimental/predicted data, which is given by

\[
CS = \mu \frac{\sum_{i=1}^{N} (x_i - \mu)^3}{\sigma^3}.
\]

where \(x_i\) \((i = 1, 2, \ldots, N)\) are data (x coordinate of black pixel in Figure 3 (b)) with \(N\) the number of data, \(\mu\) the expectation and \(\sigma\) the standard deviation. This is valid for linear eddy current excitation. The skewness of an MO image should be measured with respect to the origin (rivet center in Figure 3 (a)) for rotating current excitation. The alternative definition of the coefficient of skewness of an MO image used in this paper is the negative
ratio of the sum of the $x$ coordinates of the black pixels with positive $x$ coordinates to the sum of the $x$ coordinates of black pixels with negative $x$ coordinates, i.e.,

\[
CS_0 = \frac{\sum_{i=1}^{N} \text{sgn}(x_i) \cdot x_i}{\sum_{i=1}^{N} \text{sgn}(-x_i) \cdot x_i},
\]

where

\[
\text{sgn}(x) = \begin{cases} 
1, & x > 0 \\
0, & \text{else} \\
\end{cases}
\]

CS is then normalized as

\[
CS = \text{sign}(CS_0 - 1) \cdot (1 - \min(CS_0, 1/CS_0))
\]

with

\[
\text{sign}(x) = \begin{cases} 
1, & x > 0 \\
0, & x = 0 \\
-1, & x < 0 \\
\end{cases}
\]

such that $CS \in (-1, 1)$; CS is positive when the image skews in $+x$ direction, negative when the image skews in $-x$ direction, zero when the image does not skew.

Four test parameters are believed to affect the skewness of MO image. They are, namely, excitation current value, excitation current frequency, threshold (bias setting) and liftoff. Since increasing current value is equivalent to reducing liftoff, we do not consider the effect of liftoff in this paper. These parameters are controllable factors and incorporated in the inner array. Their variations are noise factors and incorporated in the outer array. The Taguchi method is utilized to choose the optimum set of parameters that yield an MO image with maximum coefficient of skewness and are less sensitive to their variations. The factors and the levels of each factor considered in this paper are listed in Table 1.

**TABLE 1. Factors and levels**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td><strong>Controllable</strong></td>
<td></td>
</tr>
<tr>
<td>Current value (A)</td>
<td>120</td>
</tr>
<tr>
<td>Excitation frequency (B)</td>
<td>3000</td>
</tr>
<tr>
<td>Threshold (C)</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Uncontrollable</strong></td>
<td></td>
</tr>
<tr>
<td>Variation of A (D)</td>
<td>-24</td>
</tr>
<tr>
<td>Variation of B (E)</td>
<td>-40</td>
</tr>
<tr>
<td>Variation of C (F)</td>
<td>-0.04</td>
</tr>
</tbody>
</table>
The standard OA $L_9(3^4)$, as shown in Table 2, is used for the experiment layouts of both the inner array and the outer array. Factors A, B and C are assigned to the first three columns in the inner array. Their variations, i.e., factors D, E and F, are assigned to the first three columns in the outer array. The last columns of both the inner and outer arrays are left empty.

For each combination of the simulation conditions in both the inner array and the outer array, the 3-D finite element model using $\mathbf{A}$-v formulation [6] is performed. The model has been validated by comparing the simulated image with the corresponding experimental image [6, 7]. For each row of the inner array, all trials in the outer array are performed. The resultant coefficients of skewness are then used in calculating statistical quantities, such as mean response, standard deviation and signal to noise ratio, as shown in Table 3. The total number of trials using the Taguchi method is 81 ($9^2$). This demonstrates the efficiency of the Taguchi’s experimental design when compared with the full factorial design where the total number of trials required is 729 ($27^2$).
ANALYSES

Main Effects

There are two definitions of signal to noise ratio (S/N) that are commonly used. One is

\[
(S/N)_1 = 10 \log_{10} \left( \frac{\mu^2}{\sigma^2} \right)
\]

and the other one is

\[
(S/N)_2 = -10 \log_{10} (MSD)
\]

with mean square deviation of the image skewness from the target value expressed as

\[
MSD = \frac{1}{n} \sum_{i=1}^{n} (y_i - t)^2 = (\mu - t)^2 + \sigma^2
\]

In (6) ~ (8), \(\mu\) is the mean response, \(\sigma\) is the standard deviation, \(y_i\) is the \(i\)th result in the outer array, \(n\) is the number of simulation conditions in the outer array, and \(t\) is the target value (1 for the absolute value of the coefficient of skewness).

To make the performance of MOI system robust to variations of parameters, definition (6) of S/N is preferred. Among the nine combinations of test parameters, the 7th set has the highest robustness. Definition (7) measures the deviation of quality characteristic from the target value, which is consistent with Taguchi’s quadratic loss function and utilized in the further analysis in this paper.

The main effects indicate the general trend of the influence of the factors. They are calculated by averaging the S/N ratios for each control factor at the same level. Main effects calculated from Table 3 are listed in Table 4 and plotted in Figure 4.

**TABLE 4. Main effects**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor A</td>
<td>3.066</td>
<td>4.253</td>
<td>4.319</td>
</tr>
<tr>
<td>Factor B</td>
<td>4.674</td>
<td>3.783</td>
<td>3.181</td>
</tr>
<tr>
<td>Factor C</td>
<td>4.400</td>
<td>3.958</td>
<td>3.281</td>
</tr>
</tbody>
</table>

**FIGURE 4. Main effects**
FIGURE 5. Interaction A×C

Generally the optimal set of parameters may not appear in those trial conditions in the orthogonal array, because the Taguchi’s experimental design is a partial factorial design. Optimal condition is found as the combination of the best level of each factor. Observing Figure 4, the optimal condition is Levels 3, 1 and 1 for Factors A, B and C respectively, which is not included in Table 3. A confirmation run is performed with the condition A3B1C1 and the resultant signal to noise ratio is 3.7115, much less than other values of S/N ratios in Table 3. We should note that we have neglected all the interactions between test parameters.

Two factors are said to interact when the effect of changes in one of them determines the influence of the other factor and vice versa [1]. Analyses of results show that the interaction between current value and threshold, denoted as A×C, cannot be neglected, as represented graphically in Figure 5. The combination A3C1 should be replaced by the other combination that yields the maximum S/N ratio. Since A3C1, A2C2 and A1C3 have almost the same S/N ratios, the optimal set of test parameters are A1B1C1, A2B1C2 and A3B1C3, i.e., frequency at Level 1 (3000 Hz), current value and threshold at the same level (linearly proportional). Further studies reveal the fact that using threshold proportional to the current value will yield almost identical binary MO images. The optimal combinations appear in Table 3. Hence no further confirmation runs are needed.

Analysis of Variance

Interaction A×C is assigned to the last column of the inner array. Analysis of variance is performed to estimate the percent contribution of each factor, which is helpful in determining which of the factors need to be controlled and which do not.

In the left part of Table 5, the degree of freedom of the error term (fe) is negative, which is not meaningful. In order to calculate other statistical measurements involving the division by fe, the factor that has small variance (Interaction A×C in this case) is pooled to obtain new, positive estimate of S, (sum of squares of the error term) and fe. Pooling is the

TABLE 5. ANOVA table

<table>
<thead>
<tr>
<th>Factor</th>
<th>Before pooling</th>
<th>After pooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f'</td>
<td>S</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>2.982</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1.906</td>
</tr>
<tr>
<td>A×C</td>
<td>4</td>
<td>0.940</td>
</tr>
<tr>
<td>error</td>
<td>-2</td>
<td>0.000</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>9.211</td>
</tr>
</tbody>
</table>

f: degrees of freedom  S: sum of squares  V: variance  
F: variance ratio  P: Percent contribution
process of disregarding the contribution of a selected factor and subsequently adjusting the contributions of other factors [2]. The percent contributions for the factors are listed in the last column of Table 5. Among the three test parameters considered, frequency has most influence on the performance on the MOI system in detecting the buried crack as shown in Figure 2 (a). Other factors or errors, such as interactions between parameters, have a total contribution of 41%.

CONCLUSIONS

Taguchi’s methodology of parameter design has been found to be an effective and efficient way of optimizing test parameters in NDE systems. This paper investigates the application of the Taguchi method in choosing optimal and robust test parameters for MOI inspection in detecting a critical flaw buried in the third layer. The optimal set of parameters determined for this inspection geometry is frequency at 3000 Hz with current value and threshold linearly proportionally varied. By performing analysis of variance, frequency is found to have most influence on the variance of system performance among the parameters considered. Although much of these findings are as expected this study was intended as an example of the feasibility of using Taguchi method as a tool for optimizing the parameters in any nondestructive inspection.

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REFERENCES


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